Multi-Stem Mechanised Harvesting Operation Analysis – Application of Discrete-Event Simulation

by

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: 

Date: 25 February 2009

ABSTRACT

In this study, a multi-stem harvesting operation was observed and time studies carried out on its machines. A stump-to-mill simulation model (System 1) of this system was subsequently built using a commercial simulation software package (Arena 9) and data from the time studies were incorporated into the model. Following this, another two stump-to-mill multi-stem models (Systems 2 and 3) were built using the same simulation software package and parameterised input data. These two models represented hypothetical systems which were tested against System 1 and against one another in terms of machine balance within the system, production rate and cost. System 2 used identical equipment to System 1, but practised alternative operating methods. Some of System 3's machines and operating methods differed from those in Systems 1 and 2.

The objectives of the study were to:

1. Determine whether or not commercial simulation software can be used to adequately model forest harvesting operations.
2. Gauge potential system balance, production and/or cost improvement/s achievable through application of simulation-based operation adjustments.
3. Define beneficial equipment operation and application practises for multi-stem systems.
4. Through construction and use of the commercial software package in producing forest harvesting operation models, evaluate the software's usability in terms of its applicability to and ease of use in such models, as well as its ability to meet forestry-based user requirements.

Models created using the commercial simulation software package used were found to adequately represent reality on every level, from individual work element times through machine interaction dynamics to overall system production. A difference of 0.85% in overall system production between System 1 and reality was observed. System balance was improved through normalisation of machine utilisations in Systems 2 and 3. Production improvements were achieved with the simulated volume of timber produced per month increasing by 31.1% from System 1 with three trucks to System 2 with four trucks. Cost reduction was realised, with the cost per unit of timber decreasing by 12.5% from System 1 with three trucks to System 2 with four trucks. Beneficial equipment operation and application practises were also confirmed using the simulation models, although some of these were deemed specific to the studied system's equipment and operating conditions. Usability of the commercial simulation software package in modelling forest harvesting operations was found to be acceptable, but required detailed background logic due to the extensive amount of variables and dependencies found in such operations. The software was clearly not tailored for harvesting operation modelling, but was flexible enough to be manipulated into producing the required outputs in workable format.

OPSOMMING

Tydens hierdie studie is ‘n meerstam-ontginningstelsel waargeneem en tydstudies uitgevoer op die verskillende houtinoesting toerusting. ‘n Stomp-tot-meul simulasie model (Stelsel 1) is ontwikkel, met behulp van ‘n kommersiële simulasie sagteware pakket (Arena 9), vir die ontginningstelsel en die data van die tydstudies is in die model geïnkorporeer.. Hierna is nog twee stomp-tot-meul modelle (Stelsels 2 en 3) ontwikkel met behulp van dieselfde simulasie sagteware. Hierdie twee modelle verteenwoordige hipotetiese stelsels wat vergelyk is met Stelsel 1 en met mekaar in terme van die balanseering van toerusing binne die stelsel, produksie tempo en koste. Stelsel 2 het dieselfde toerusting as Stelsel 1, maar verskillende operasionele metodes is voorgestel en gebruik. Sommige van Stelsel 3 se masjiene en operasionele metodes verskil van die van Stelsels 1 en 2.

Die doelwitte van die studie was:

1. Evalueer of kommersiële simulasie sagteware gebruik kan word om bosbou operasies en veral houtinoesting operasies, doeltreffend te modelleer.
2. Bepaal of potensiële stelsel balans, produksie en/of koste verbetering/e bereik kan word deur die toepassing van simulasie gebasseerde operasionele aanpassings.
3. Definieer voordelige toerusting en toepassings gebruike vir meerstam-stelsels.
4. Deur die konstruksie en gebruik van die kommersiële sagteware pakket in produksie van bosbou operasionele modelle, evalueer die sagteware se bruikbaarheid in terme van toepasbaarheid en gebruik in bosbou operasionele modelle, sowel as moontlikheid om bosbou gebasseerde gebruikers vereistes te kan bevredig.

Die modelle wat geskep is met behulp van kommersiële simulasie sagteware het realistiese operasies, vanaf individuele werkselemente tydsduur tot masjien interaksie dinamiek en totale stelsel produksie, voldoende gesimuleer. ‘n Verskil van 0.85% in totale stelsel produksie tussen Stelsel 1 en werklike operasies is waargeneem. Stelsel balans is verbeter deur die normalisering van masjien gebruik in Stelsels 2 en 3. Produksie verbeteringe is behaal, met die gesimuleerde volume hout wat maandeliks ontgin is, het toegeneem met 31.1% vanaf Stelsel 1 met drie houtvervoer vragmotors tot Stelsel 2 met vier vragmotors. Koste besparings is bereik met die koste per eenheid hout wat met 12.5% vanaf Stelsel 1 met drie vragmotors na Stelsel 2 met vier vragmotors, verlaag het. Voordelige toerusting gebruik en toepassing is ook bevestig met die simulasie modelle, maar sommige van hierdie gebruike was spesifiek tot die bestudeerde stelsel se toerusting en operasionele omstandighede. Die gebruik van kommersiële simulasie sagteware in die modellering van bosbou operasies was aanvaarbaar, maar vereis komplekse logika weens die groot aantal veranderlikes en onderlinge afhanklikhede in bosbou werksaamhede. Dit is duidelik nie gemaak vir bosbou opersionele modellering nie, maar aanpasbaar genoeg om gemanupileer te word om die vereiste uitsette in ‘n werkende format te lewer.

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1. INTRODUCTION

1.1. Background and Justification

Mechanisation of South African (SA) timber harvesting operations has been a gradual, albeit slow process over the past ten years. There has, however, been a recent acceleration in the establishment of these systems in the industry. This is primarily due to potential reduction in timber breakage, improvement in wood utilisation and greater value recovery (Kewley and Kellogg, 2001), as well as the drive for improved safety of harvesting operations. Although the volume of timber harvested by mechanical equipment in the country is on the increase, there are few (if any) national benchmarks and proven best operating practises on which these systems can be grounded. As a result, inefficiencies and unnecessary variation within and between operations are common. This problem resulted in the demand for studies in system comparison and improvement, which would hopefully lead to identification of improved operating practises and systems in SA forest harvesting operations. One relatively recent mechanised application in the country is the multi-stem system, employed in SA pulpwood operations, which is the focus of this study.

The operational problem to be addressed in this thesis is one of mechanised harvesting system representation and improvement through application of simulation techniques. Simulation modelling facilitates detailed manipulation and testing of operating practise and system combination alternatives on a trial-and-error basis within the safety of a computer programme. It therefore has no bearing on the real world system until the final improved simulated system is decided upon and implemented. This ensures as far as possible that any changes made to the real system will be positive and beneficial.

This thesis stands as the first timber procurement simulation study to be carried out in SA – an advancement in the country's precision forestry research field.

1.2. Objectives

A model of a multi-stem mechanised harvesting and transport operation is to be constructed using simulation software. Another two models representing hypothetical multi-stem systems will also be constructed through the application of operations research (OR) simulation techniques.

Using the simulation models and their outputs generated in the study, the following will be addressed:

1. Determine whether or not commercial simulation software can be used to adequately model forest harvesting operations.
2. Gauge potential system balance, production and/or cost improvement/s achievable through application of simulation-based operation adjustments.
3. Define beneficial equipment operation and application practises for multi-stem systems.
4. Through construction and use of the commercial software package in producing forest harvesting operation models, evaluate the software's usability in terms of its applicability to and ease of use in such models, as well as its ability to meet forestry-based user requirements.

1.3. Scope

Framework for this study falls within the field of simulated multi-stem timber procurement of *Eucalyptus* pulpwood, with focus on system balance, monthly production and cost. Related fields (such as post-harvest silviculture and management) and concerns (such as social and environmental issues) will not be included as major study points. Simulation models built within the study will be tree-to-mill models, beginning with the forest stand to be felled, and ending with secondary transport taking timber to the mill.

2. MODELLING AND SIMULATION

2.1. Modelling

Modelling is the broad term ascribed to the representation of an entity, object or system in any form other than itself. Abstraction is required during modelling (Figure 1) and reversal of the abstraction is necessary for model interpretation (Taha, 2003). Models can be prescriptive (represent a proposed system) or descriptive (represent a current system).

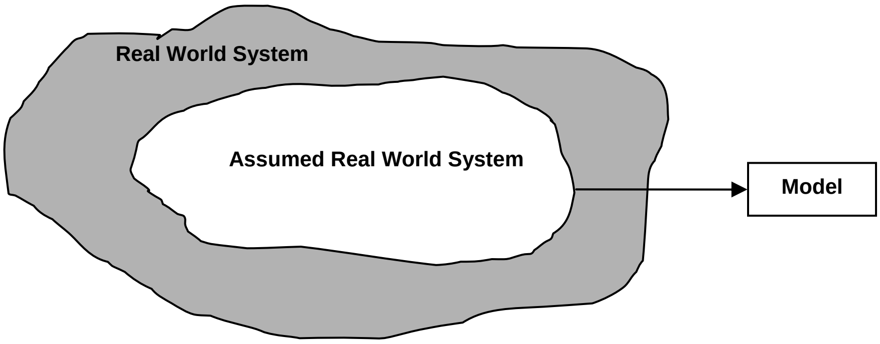

FIGURE 1: Models are Abstractions of Reality (Taha, 2003).

Abstraction of a real world system is achieved through identifying and incorporating into the model only the dominant and/or relevant factors that control the real world system's behaviour (Taha, 2003). Through this, the real world system can be represented to an acceptable degree of accuracy.

Models vary in the degree to which they represent reality. Isomorphic models comprise an exact agreement between the elements of the model and the object itself. Exact relationships and interactions between the elements are preserved in these models. Homomorphic models are similar to the real system in form, but different in fundamental structure. This difference can be attributed to abstraction in representation. Simulation models are homomorphic, but the degree of isomorphism (extent to which the model agrees with reality) needs to be stated and tested if conclusions from the model are to be drawn. This process is known as model validation (Banks, 1998).

2.2. Simulation

2.2.1. Simulation Defined

Operations' research (OR) incorporates creative scientific research into fundamental properties of operations (Hillier and Lieberman, 2005). Problems are generally approached with an operation optimisation or improvement outlook. Queuing and simulation together form one of the branches of OR (Taha, 2003), but are not limited exclusively to OR. Simulation has, over the past two to three decades, consistently been reported as the most popular OR tool. It refers to a wide compilation of methods and applications to predict real system behaviour through numerical evaluation using software designed to replicate system operations and/or characteristics, usually over time (Kelton *et al.* 2003). It involves the construction of a model of a real system, and experimenting with that model to understand the system's behaviour and/or evaluate operation alternatives (Pegden *et al.* 1995). Banks (1998) defined simulation as "The imitation of the operation of a real world process or system over time". He went on to note that simulation "involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented". Simulation can therefore be seen as experimentation with a model of a real world system, given certain starting conditions, to observe behaviour of the model and relate the behaviour back to the real world system which the model represents. Asikainen (1995) claimed simulation to be, "The next best thing to observing a real system". It is one of the most powerful tools available for evaluation and design of complex operating systems (Gallis, 1996).

Simulation is not an optimisation technique, but rather provides estimates of system performance through modelling (Rantanen, 1987 cited in Asikainen, 1995; Goulet *et al.* 1980; Gallis, 1996; Hansen *et al.* 2002; Hillier and Lieberman, 2005). It can thus be used to evaluate different alternatives within the system, acting as a tool for system improvement, but there is no guarantee that the final improved system is in fact an optimisation of the original (Hillier and Lieberman, 2005).

Simulation application is generally used in the analysis of complex real world systems which cannot be assessed using analytic OR techniques due to system component interaction complexities. Numerous built-in parameters, variables and functions have led to simulation software coping with these interactions which other analysis tools could not (Ziesak *et al.* 2004).

2.2.2. Simulation in Perspective

Until 1960, simulation models were all built in general purpose programming languages such as Fortran, Pascal (Banks *et al*. 1991) and Basic. These languages offered great flexibility, but were extremely slow and required user fluency (Ojala, 1992). Simulation languages (such as GPSS, SLAM and SIMAN), designed to facilitate programming of simulation models were introduced in 1961 (Asikainen, 1995). These languages offered concept apparatuses for model construction and resulted in reduced encoding required by the user and simplified simulation implementation (Andersin and Sulonen, 1974 cited in Asikainen, 1995). Simulators (e.g., WITNESS, STARCELL and SIMFACTORY) succeeded simulation languages as computers and computer programmes became more powerful. Simulators provide a graphical interface which allows the user to call up and build pre-programmed statements into the simulation language (Banks *et al.* 1991). The first simulators were developed in the early 1980's for modelling of manufacturing processes, but are now being used in numerous applications of systems and processes (Asikainen, 1995). Programming, conditional routing, entity attributes, global variables and interfacing to other software are some of the stout qualities associated with these programmes (Banks *et al.* 1991).

Simulation is made up of many branches, each of which is classified according to the type of model it produces. Figure 4 shows a breakdown of several modelling techniques (not all techniques are included). The simulation method to be used in this study (i.e., discrete-event simulation) can be identified by following the shaded blocks.

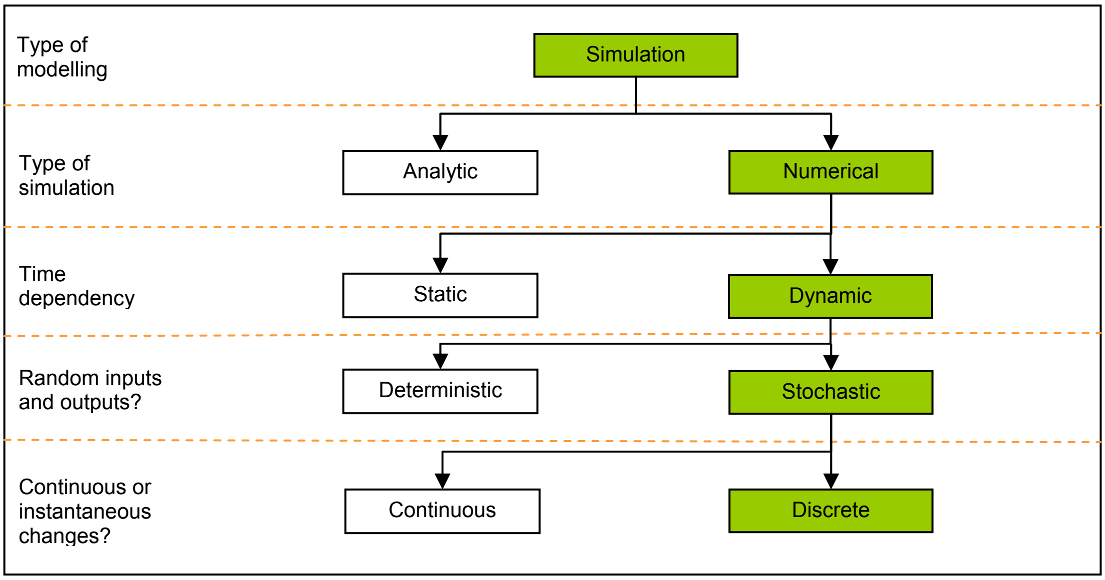

FIGURE 2: Breakdown of Simulation Methods.

2.2.2.1. Dynamic and Static Simulation

Dynamic simulation means that time plays a role and is included in the model, whereas static simulation means that time has no bearing on the simulation, so it is not explicitly included (Kelton *et al.* 2003). A static simulation model will thus represent a system at a single, specific moment in time. A dynamic model, on the other hand, will model the system as it changes over time (Asikainen, 1995).

2.2.2.2. Stochastic and Deterministic Simulation

Stochastic simulation models have at least some random input incorporation (built in through random number generators and probability distributions), resulting in modelled output data not necessarily being identical to real world data. Simulation runs, therefore, will also produce different output data for each replication, even though the inputs remain the same. Deterministic models have no random inputs, meaning that a certain set of input data will always give the same set of output data (Asikainen, 1995) and the output data will be the same for each modelled replication.

2.2.2.3. Continuous and Discrete Simulation

Kelton *et al.* (2003) noted that continuous models describe the state of the system as it changes over time (e.g., constantly fluctuating water level in a reservoir). State variables are continuously changing in these models (Asikainen, 1995). In discrete (activity-oriented) models, instantaneous changes of the state variables occur at a finite number of points in time in response to certain discrete occurrences, known as events (Asikainen, 1995; Gallis, 1996). Event points are linked together in sequence as time moves forward, representing a system as a series of photographs would a movement. This approach can be described as a combination of queues and processes (Hansen *et al.* 2002). Times between events are defined by activity duration/s. During simulation runs, the software scans model activity and progression for conditions of starting or ending an activity. When a prescribed (starting or ending) condition is met, appropriate action is taken in that instant (Gallis, 1996), representing a discrete point/event (Figure 5).

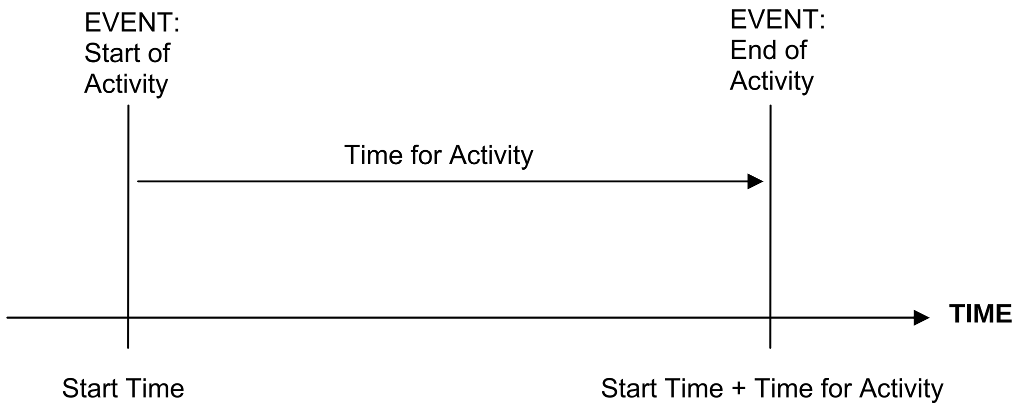

FIGURE 3: Activities and Events in Discrete-Event Simulation (Adapted from Gallis, 1996).

2.2.3. Simulation Application

Common reasons for simulation studies include (Kelton *et al.* 2003):

- Analysis of a system's operations before it is implemented, thus helping to minimise unnecessary cost incurrence.
- Planning a proposed system to identify and overcome operational and/or logistical problems before the system is implemented.
- Improvement of an existing system or its components.
- Identifying and studying critical parameters in a system.
- Evaluation of possible alternative scenarios.
- Providing a complete system understanding for complex operations.

The study in this thesis will focus on an existing real world system, and attempt to identify improvements for the system using simulation. Figure 6 illustrates how potential system improvement can be achieved through the application of simulation.

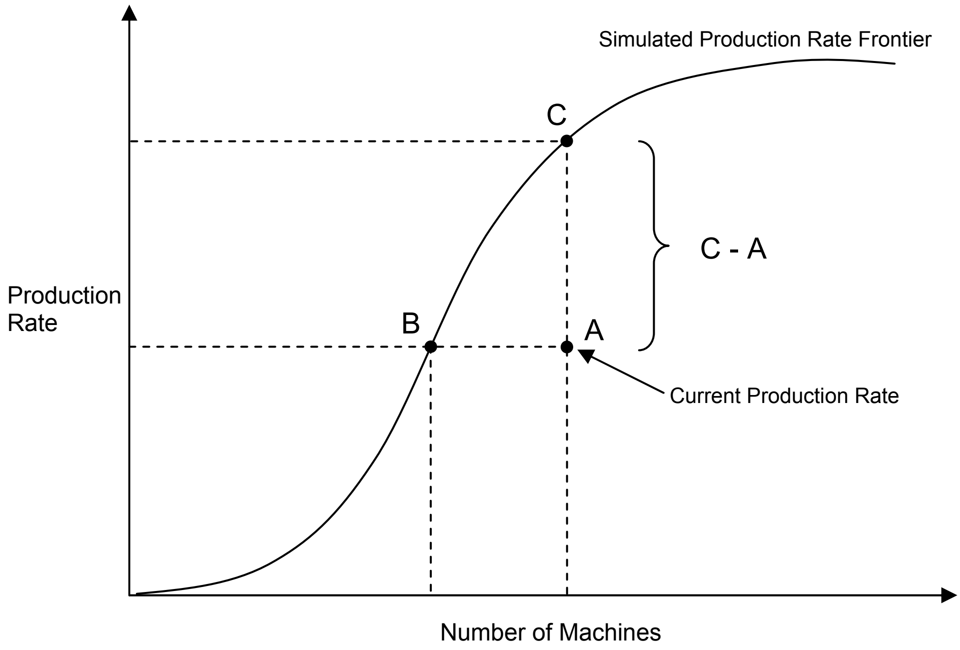

FIGURE 4: Simulated Production Rate Potential of a Hypothetical System (adapted from McDonagh, 2002).

The hypothetical system described in Figure 6 is currently operating at a production rate equivalent to point A. A simulation study may reveal that the same system could achieve a production rate of C if specific adjustments are made to work methods. This means that according to the study, it is currently under-producing at a simulated rate of "C-A" based on its capacity. This deduction can now result in the implementation of an improved system in one of two ways. First, the current system's operating techniques can be improved, increasing production to point C. Second, if a production rate of A is all that is required of the system, the number of machines can be reduced and the operating methods of the remaining machines improved so that the system will be described by point B, thus reducing system capital and cost (McDonagh, 2002). Note should be taken that the simulated production frontier will, in all likelihood, not be equal to the unknown optimal system production frontier. This is because system improvement in simulation studies is carried out by the user on a trial-and-error basis, the effectiveness of which is limited by time availability and user creativity (Goulet *et al.* 1980). Simulation involves user-based analysis of potentially feasible alternatives to the current situation (Randhawa and Scott, 1996), but cannot auto-generate solutions. As mentioned in Section 2.2.1, it is not an optimisation tool, but an analysis and alternative scenario testing aid which often leads to system improvement. This is evident through the increased production rate from point A to point C. Point C may not be the optimal point, but it will be far closer to the true optimal production frontier than the original system operating at point A.

2.2.3.1. Advantages and Disadvantages of Simulation

As is the case with all modelling and operation improvement tools, simulation has several benefits and several shortcomings. The more prominent advantages and disadvantages are listed below:

Advantages of simulation:

- Allows a modelled study of an existing real world system's performance under various conditions in situations where direct experimentation with the real system would be costly, disruptive or impossible (Law, 1986; Ziesak *et al.* 2004; Asikainen, 1995).
- Facilitates comparison between simulated scenarios and systems.
- Simulated time compression allows long simulation runs to be carried out in a short time span, making data collection from the model cheap and efficient (Render and Stair, 1992; Ziesak *et al.* 2004).
- Alternative scenarios can be tested without interrupting the real system (Asikainen, 1995).
- Experimental condition control is often better maintained in simulation than in an experiment with the real system (Law and Kelton, 2000).
- Simulation of proposed systems can result in the identification and addressing of problems before the real system is implemented, minimising real system start-up time (Kelton *et al.* 2003).
- A system-wide view of the effects of changes to a specific part of the system or to the system as a whole can be modelled (Law, 1986; Hansen *et al.* 2002; Kelton *et al.* 2003).
- Potential benefits of simulation include, amongst others, increased throughput, reduced in-process inventories, improved machine and/or worker utilisation, reduced capital requirements, reduction of unnecessary activities and cost reduction per entity (Law, 1986).

Limitations of simulation:

- Simulation does not auto-generate optimal solutions to problems, it just predicts the outcomes of certain measures and inputs.
- Each model is specific to a certain system and a defined problem (Ziesak *et al.* 2004). Its solutions thus do not always apply to all related systems.
- Simulation is an experiment, meaning that it is not guaranteed to solve the defined problem (Hannus and Louhenkilpi, 1976 cited in Asikainen, 1995).
- Analysis quality and reliability depend on model quality and input data accuracy (Asikainen, 1995). An inaccurate model or poor data thus has the potential to result in decisions and actions being taken in reality, based on incorrect model outputs.

- Data acquisition can be a long, costly process (Nelson, 2003).
- Data should be up to date and accurate, which is not always possible, especially with systems which have not yet been implemented in reality.
- Verification and validation of complex models can be a tedious task (Nelson, 2003).
- Running of large-scale, long-term forecasting models can exceed the scientific credibility of the data (Nelson, 2003).
- Detailed simulation models can be costly and take a large amount of time for input data collection and model construction (Law and Kelton, 2000; Render and Stair, 1992; Thesen and Travis, 1992, Asikainen, 1995).
- The extensive amount of numbers produced by a simulation study often leads to a tendency to rely on the study's results more than is advisable (Law and Kelton, 2000).
- Software can be expensive.
- The analyst needs to have good understanding of the system being simulated and the simulation software to be used.

2.2.4. Simulation Terminology and Concepts

Simulation models are constructed using a variety of components set up in mutually interpretable form between model logic and the analyst. These components ultimately govern exactly how the simulation will run and the nature of outputs to be collected. Some of the more important components of Arena 9 simulation software include (Kelton *et al.* 2003):

- Entities: These are the dynamic objects within the simulation (e.g., trees in a harvesting operation). They are generally created when they enter the model, follow a specific path through the model, and then are disposed of when they exit the model.
- Attributes: An attribute is a characteristic common to all entities, but the value of that characteristic may differ from entity to entity (e.g., the merchantable volume of a tree).
- Variables (a.k.a. State Variables or Global Variables): These are instantaneous measurements of specific characteristics of the system. They apply to the system as a whole, and can be values which change over time (e.g., the number of entities in the system) or remain constant (e.g., the capacity of a machine).
- Resources: Units which change the shape, form or state of entities in some way (e.g., machines in a timber harvesting operation).
- Statistical accumulators: Counters which measure intermediate statistical variables within the model as the simulation progresses (e.g., counting the number of entities processed by a resource).

- Events: An event is an occurrence which takes place in an instant of simulated time. It may alter the state of the system by resulting in a change of attributes, variables or statistical accumulators (e.g., the detachment of an entity from a resource). The entire model is centred on these events in discrete-event simulation model runs.
- Processes: A process is made up of an entity seizing a resource, delaying it for a specific period and then releasing it again. Entities are in some way changed after having been processed.

Simulation world view deals with how a real world system is conceptualised in computer language. It is thus the implicit view of the simulation software that the analyst must follow in order to implement a real world system's behaviour (Gallis, 1996). It incorporates all simulation model components and describes how they collectively represent reality. A typical simulation world view is laid out in Figure 7.

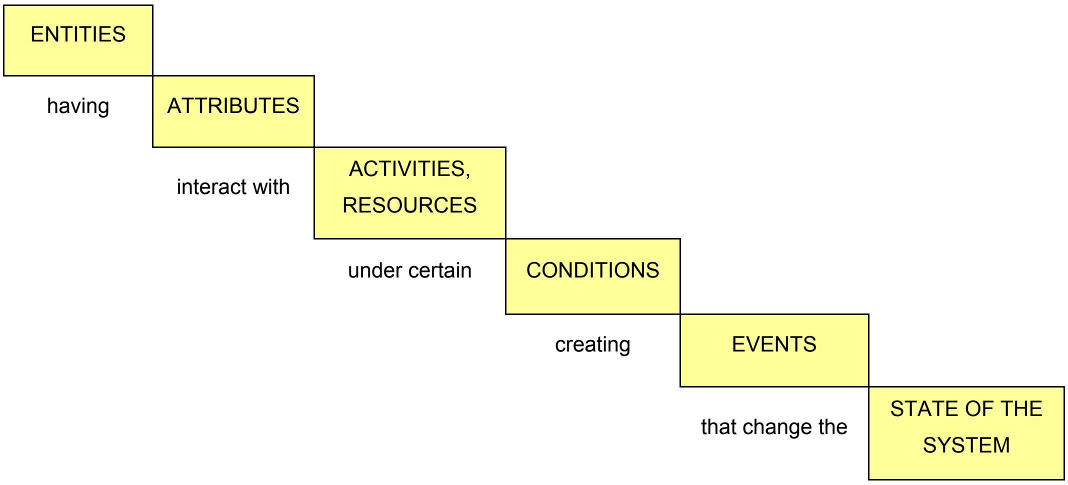

FIGURE 5: Simulation World View (Shannon, 1975).

In the approach to simulation taken in this study, entities (e.g., trees) drive a simulation run by competing for resources (e.g., machines), and not the other way around (Kelton *et al.* 2003). A resource has a specific capacity which waits for an entity to seize it. Processing of an entity by a resource therefore incorporates the entity seizing the free resource, delaying it for the appropriate processing time and releasing the resource so that it can be seized by another entity. In this manner, entities progress through the simulation model until they reach the end of the model and are disposed of.

2.2.5. Data Acquisition and Incorporation Methods

For a discrete-event simulation model to represent reality, some form of data or information regarding time consumption per activity of the real system is required. Simulation software uses this data or information to generate observations which ultimately determine how the model will run and what its outcomes will be. Taylor *et al.* (1995) stated that apart from model validity, the success of any computer simulation model depends most heavily on the software's ability to accurately characterise input data through best fitting probability distribution functions, as well as to maintain any correlation among the variables. Simulation programmes generally employ several curve description methods for internally describing input data. These data description functions are then used to represent the original data and their distribution.

Kellogg *et al.* (1992) stated that input data of good quality, determined from an accurate definition of events are vital for credible simulation output. Unfortunately, however, data acquisition may not be possible if data for the real system are not available nor collectable, or the real system has not yet been created. Methods of collection thus require different approaches depending on the circumstance and data credibility often varies according to the collection method.

2.2.5.1. Data are Available or Collectable

If data are available or collectable, some of the more common sources include:

- Previous studies (Asikainen, 1995). If studies have been carried out on the same system in the past, it means historical data and information are available. This method does carry disadvantages, however, such as data potentially not being up to date, data accuracy being questionable and data collection potentially having used different work elements to what is required.
- Existing reports (Asikainen, 1995) and external sources (such as consultants). This can require incorporation of a correction factor to more accurately describe the system being studied, depending on data relevancy to the system.
- Observational data (Kelton *et al.* 2003). Personal observation of the system is time consuming but allows the analyst to be specific in data quantity, type and accuracy. A disadvantage of this method is that it may only represent the system under certain conditions, rather than on a broad scope. An advantage is that the analyst may identify potential system improvement methods during data collection which can be tested in the simulation study.

One of two options can be used for data incorporation into the model if the data were available or collected, namely theoretical distribution or empirical distribution (Kelton *et al.* 2003). Theoretical distribution involves data description using a smooth curve (which is defined by a specific function). It may result in tail values which fall outside of real world observation data being incurred in simulation runs. Two of its biggest advantages, however, are that it requires little computer memory allocation and it allows the reproduction of random observations within the model. Empirical distribution is generally only used if no adequate theoretical distribution can be fitted to the data. It only allows simulated observations within the real world observed data range and requires greater memory space.

2.2.5.2. Data are not Available or Collectable

If data are not available or collectable, some form of data generation is required. In such cases, it should be made clear that input data were made up of estimates when results are presented (Asikainen, 1995). Model validation is often difficult when using these data collection methods as there is nothing on which to benchmark simulation outputs. If data are not attainable, one or a combination of the following methods can be used:

- Estimates and educated guesses (Asikainen, 1995). This allows almost instantaneous "data" collection, but accuracy can be questionable.
- Manufacturers' claims (Asikainen, 1995). Manufacturers usually provide operation estimates for their equipment, but these estimates often tend to be optimistic.
- Theoretical considerations. Accepted theories found in previous literature may be used (Kelton *et al.* 2003).
- Comparison with other, similar operations (Asikainen, 1995). Some type of conversion is generally required for the data to represent the specified system more accurately in this case.

2.2.6. Random Number Inputs and Random Observations

Computer simulation models aim to imitate the behaviour of real world systems as a function of time through numerical evaluation (Law, 1986; Render and Stair, 1992; Asikainen, 1995). Aedo-Oritz *et al.* (1997) claimed that the most important feature of simulation output is for it to be able to reproduce the randomness of an actual system and to predict its performance. This is true for all stochastic models.

The logic behind dynamic stochastic simulation is that if a probability distribution for each activity's time expenditure (derived from data) is known, random observations from those probability distributions can be drawn and strung together to describe the system's operation over time (Taylor *et al.* 1995). Simulation software programmes use several methods to generate random observations from the respective statistical distributions. Before observations can be drawn, however, random numbers need to be created within the model. In many simulation programmes, this is made possible through one or more built-in random number generators which, during simulation runs, produce random number streams. These streams allow stochastic simulation models to combine user-input probability distributions with random numbers to generate artificial observations within the model, hence imitating real world randomness. Changing the initial random number seed for each replication in a terminating stochastic simulation ensures unbiased, independent observations in each replication (Baumgras *et al.* 1993).

2.2.7. Model Verification and Validation

Law (1986) described an acceptable simulation model as a model which would ideally be accurate enough that any conclusions derived from the model would be consistent with those drawn from testing the real system. One should, however, bear in mind that a model is an abstraction of reality. This means that even a perfect simulation model will not generate results which agree exactly with the real situation, but it should yield an adequate approximation of it (Rummukainen *et al.* 1995). Model verification and validation are two tools used in simulation studies to ensure as far as possible that this is the case. Model verification involves debugging of the simulation model until the analyst is confident that the model logic contains no anomalies. Validation refers to determining whether the model and its outputs accurately represent the real world system (Asikainen, 1995).

In verification, the question of whether or not the model been built correctly is answered. In this phase, syntax errors, model logic, compiler errors and run-time errors are corrected (run-time errors are errors which only become apparent during the running of the simulation model). If no errors occur, it does not mean the model is error-free, it means the no errors have been manifested with the given data set. Model animation and running the model in a step-by-step manner are extremely useful in identifying and ironing out mistakes in this phase (Kelton *et al.* 2003).

In validation, the issue of whether or not the correct model been built is addressed. It involves evaluation of how well the model describes the real system (Rummukainen *et al.* 1995). This is generally carried out by running the simulation and then comparing simulation observations with real world observations.

2.2.8. Arena 9 Simulation Software

The simulation software programme used in this study was Arena 9. It is made up of a combination of general purpose programming language, simulation language and simulators. It offers interchangeable templates of different types of graphical simulation modelling and analysis modules which can, in most cases, be combined in the same model (Kelton *et al.* 2003). The software is based on the SIMAN/Cinema system (Pegden *et al.* 1995). It is a Visual Interactive Modelling System, meaning that the model is built using flowcharting methodology to explain system logic, which the programme then uses to generate underlying model code (Hansen *et al.* 2002). Model animation is also possible with this software. Arena has been most widely used in the manufacturing environment, but has recently been applied in transport and many other spheres (Hansen *et al.* 2002). It has been used in SA to model sugar cane harvesting and transport systems (Hansen *et al.* 2002), but has not been applied to forestry operations in the country to date.

Models in Arena are represented on the world space, which is a synthetic digital area of abstract size in which flowchart depiction of the model is created. The area is made up of x and y coordinates which have no physical meaning or units (Kelton *et al.* 2003). Flowchart modules and data modules are the building blocks in Arena. They define the system to be simulated. Flowchart modules describe the dynamic processes of the model (nodes through which entities originate, flow and leave the model). They are displayed in the world space during model construction. Data modules define the characteristics of various process elements (e.g., entities, resources and queues). They are displayed in the model spreadsheet window (part of the background model logic). Connectors are the lines which join flowchart modules in the world space. In animation, entities run along the connectors from module to module in zero simulated time (Kelton *et al.* 2003).

The basic path an entity follows if being served by one resource in the system is as follows:

Entity arrives → Entity joins queue (if any) → Entity served → Entity exits system

3. FOREST HARVESTING OPERATIONS

Forest harvesting operations encompass all technical and commercial activities required for the provision of wood raw material from the forest to the mill (Stenzel *et al.* 1985; Sundberg and Silversides, 1988). Procedures which traditionally take place in South African stump-to-mill timber procurement operations include felling, primary transport, delimbing, debarking, cross-cutting, loading and secondary transport. These steps are not necessarily in the correct order of sequence, depending on the type of system employed. Extended primary transport and secondary intermediate transport are also carried out in harvesting operations in SA, but these are more circumstantial.

3.1. Forest Harvesting Operation Dynamics

In forest harvesting operations, the output of one phase is the input of another phase (MacDonald, 1999). This means that the operation of a machine affects not only itself, but also the operation of some or all other machines in the system. This phenomenon has given rise to the necessity for correctly sized timber inventories between phases, accurate equipment balancing, correct system selection and correct equipment combination. Inventories between activities are vital as they act as buffers, balancing interactions of machines making up the system (Asikainen, 1995). This is especially true of harvesting systems which are made up of machines linked in series (such as multi-stem systems). If inventories are insufficient, a delay in one stage of the chain is more likely to have adverse effects on other operations both higher up and lower down in the series (Asikainen, 1995). McDonagh (2002) concluded that blockages and bottlenecks in harvesting operations, as well as starvation delays, are often limiting to system production if inventories are managed at low levels. These delays result in increased unproductive time, which leads to increased cost per unit of timber. If inventories are over-sized, however, costs are incurred in the form of decreased productivity, timber damage, timber quality degradation, fibre loss and site damage (Asikainen, 1995).

Maintaining buffer level consistency and reduced stock-related delays requires effective equipment balancing. Balancing aims to bring the potential output of each activity within the timber procurement line to as similar a capacity as possible, with the most expensive activities being the best utilised within the system’s operating. This is carried out by assigning the correct number of machines per task according to machine capabilities and system demands, as well as adjusting work methods and scheduled work time parameters to ensure timber flow through the system is as consistent and continuous as possible.

Machine interaction is the activity or activity outcome of one machine in a system affecting the activity or activity outcome of another machine within the same system (McDonagh, 2002). This is determined primarily by the equipment combination making up the system. Corwin *et al.* (1988) identified equipment combination as one of the key factors in determining the success or failure of a forest harvesting system. Randhawa and Scott (1996) claimed that equipment selection in harvesting operations is affected by harvesting environment, stand characteristics and transport distance. Added to this, factors such as potential equipment interaction dynamics, timber volume to be extracted, required buffer levels and balancing option selection all influence appropriate selection of equipment. Machines making up a suitable harvesting system should be applicable and/or adaptable to the environmental condition/s, and work well in combination with one another.

4. SIMULATION OF FOREST HARVESTING OPERATIONS

Forest harvesting operation simulation models were launched in the late 1960’s as a method of evaluating forest machine concepts (Goulet *et al.* 1979; McDonagh, 2002).

4.1. Applicability of Simulation to Forestry

Since the birth of forest harvesting operation simulation, computers have aided in decision-making and improvement of system cost and production factors by balancing equipment within systems and assessing potential advances associated with stand and machine variables (Reisinger *et al.* 1988). Simulation allows the researcher to standardise certain variables so that focus can be directed towards the variable/s of interest, leading to un-confounded results (Eliasson, 1999). It has been proven as an acceptable method of harvesting operations assessment in a wide range of machine, harvest and stand condition variables (Wang and Greene, 1999; Hartsough *et al.* 2001; Wang and LeDoux, 2003). Webster (1975) claimed that simulation was the most suitable method for harvesting operation analysis due to the complications of timber harvesting systems disqualifying the applicability of any other potential methods. He went on to say that it serves as an accepted method of assessing a wide range of system configurations, operating environments and different timber utilisation options. Stuart (1981) concluded that only computer simulation had the capacity required to cope with the problems and adapt to the needs of the user in analysing forest harvesting systems. Wang and Greene (1996) reported that simulation is a feasible method for exploring operation and working patterns of machines in forest stands. Hool *et al.* (1972) made the following statement regarding pulpwood harvesting simulation: "Pulpwood harvesting systems are too complex to visualise easily, respond too slowly to perturbations and are too expensive to experiment with. Consequently, simulation is particularly applicable." Numerous interdependent variables in timber procurement, however, can make simulation difficult (Meimban *et al*, 1992).

4.2. Commercial Industrial Simulation Software in Forestry

Bruchner (2000) (cited in Ziesak *et al.* 2004) found that commercial industrial simulation software could be adopted for use in forest harvesting operation simulation. Ziesak *et al.* (2004) identified the greatest challenges facing an analyst when applying industrial simulation software to these operations to be the following:

- Forestry works on far bigger areas than industrial facilities.
- There is potential for far more parameters in forest models due to the extensive scope of harvesting operations.

- Harvesting operations are mobile (including both within-stand moves and between-stand moves)
- Machine movements have to follow specific, sometimes unconventional rules, which are determined by the system and the operation thereof.
- Complex logic rules which differ from those of industrial production are required to describe harvesting operations.

Ziesak *et al.* (2004) also concluded that software produced for commercial industrial simulation purposes had the capacity to cope with modelling of complex forest harvesting operations.

4.3. Simulation Model Classification for Forest Harvesting Operations

Resource analysis simulation models in forest harvesting operations can be classified either as phase models or tree-to-mill models (Figure 8) (Randhawa and Scott, 1996). Such models focus specifically on resources (machines) in terms of allocation, manipulation and/or improvement. They do not concentrate on entity allocation, as would be the case in entity analysis simulation models. Tree bucking improvement through efficient utilisation of trees into finished products is an example of what has been carried out in entity analysis simulation studies. In such studies, the entities, not the resources, are the points of interest (Pnevmaticos and Mann, 1972; Mendoza and Bare, 1986; Sessions *et al*. 1989). Phase models focus on a specific part of the harvesting or logistics process (Wang and Greene, 1999). They do not consider the harvesting operations value chain or the potential implications which could be incurred outside their scope of study. Tree-to-mill models instead include all operations involved from tree felling to wood arrival at the mill (Asikainen, 1995; Wang and Greene, 1999). They aim to improve machine operating methods and interactions between machines, as well as minimise system bottlenecks, thus improving the system as a whole. These models cover the largest study level, and recognise the importance of studying components of the supply chain as inter-dependent units (McDonagh, 2002).

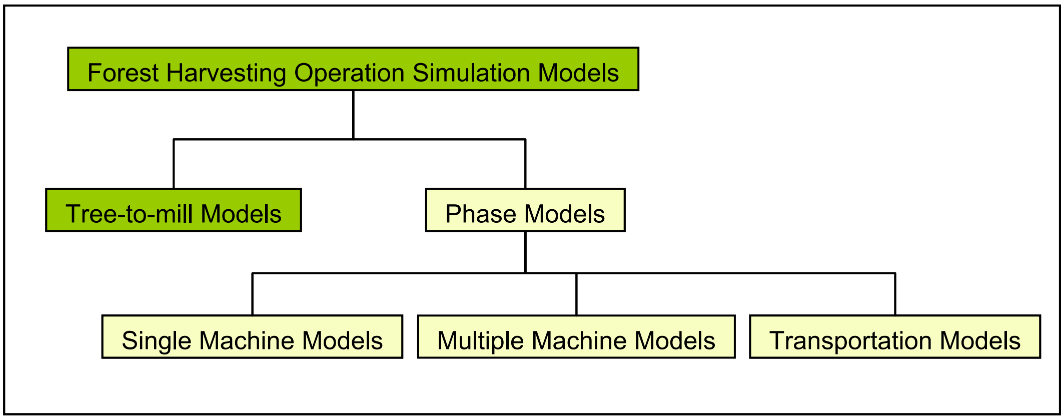

FIGURE 6: Types of Forest Harvesting Operation Simulation Models.

5. METHODOLOGY

5.1. Research Area

The Zululand coast of Kwa-Zulu Natal represents one of SA's major forestry plantation growing areas (Gardner, 2001). Rainfall distribution for the region as a whole is good, with between 35 and 40% of the annual precipitation falling in winter (dry) months (Herbert and Musto, 1993). Topography is generally flat, comprised mainly of Quarterly aeolianite and alluvium (Herbert and Musto, 1993).

Kwambonambi is a town situated on the Zululand coastal plain, approximately 30 km north of Richards Bay (Figure 9). It can be found at the co-ordinates 28°36'00"S, 32°04'60"E, at an altitude of 80 m above mean sea level. It has a mean annual temperature of 21.8°C, a mean annual precipitation of 1 015 mm, and is characterised by deep, weak, sandy soils with less than 5% clay content, developed from Aeolian sands (Smith, 1998; Smith and du Toit, 2005). It has a sub-tropical climate and an average rotation length for *Eucalyptus* pulpwood of seven to eight years.

This study focuses on a harvesting site within 2 km of Kwambonambi. The site is made up of Mondi Business Paper's D56, D60, D62 and D63 compartments, which stand adjacent to one another. Terrain classification for the harvesting site can be defined as 222.1.1 according to the guidelines in Erasmus (1994). The first three numbers of this classification indicate that in dry, moist and wet conditions, the bearing capacity of the soil is good. The following number describes ground roughness (with reference to the presence and incidence of obstacles), which is smooth. Slope is portrayed by the last number. The site has a slope of 2% and is thus classified as being level (between 0 and 11%).

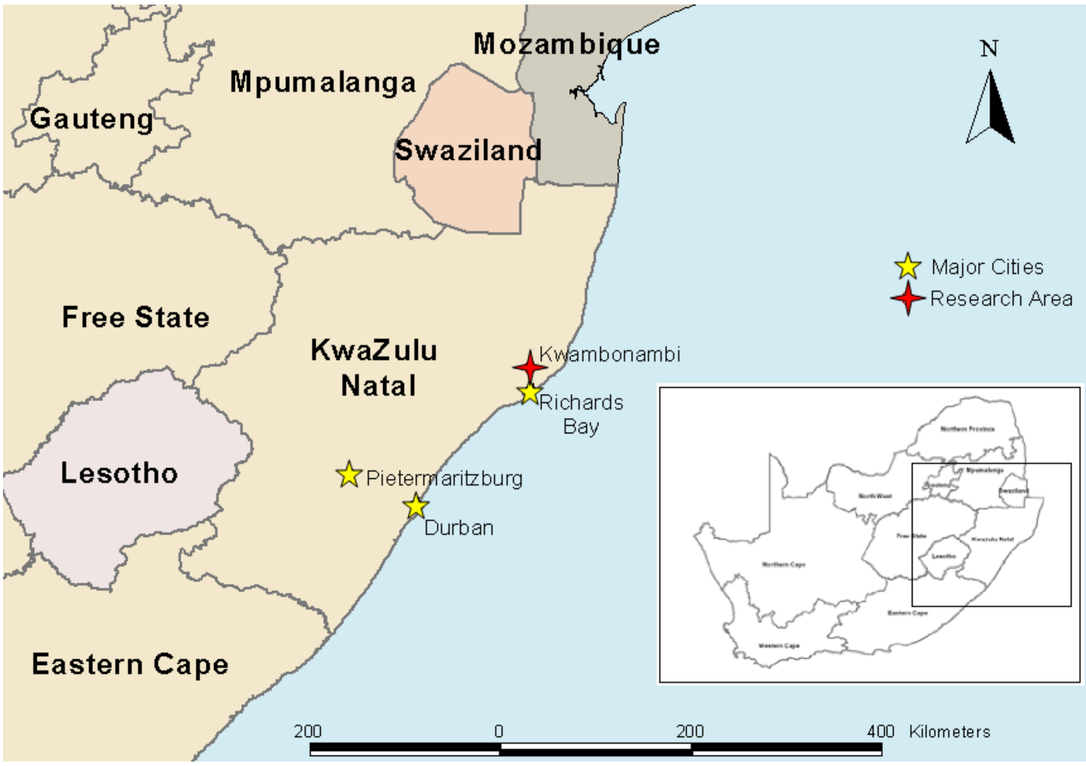

FIGURE 7: Map Showing Research Site and Major Cities in Kwa-Zulu Natal

Tree sizes at clearfelling age were similar between the even-aged clones. Average stand density was 1 145 stems/ha. The four compartments in which the study was carried out were all planted at the same time with *Eucalyptus grandis X camaldulensis* at a spacing of 2 m by 3 m. A compartment width of 850 m was shared by all compartments and the secondary transport road ran along the western boundary of all compartments. As a result, compartments were consolidated and treated as a single compartment in the harvesting operation. Secondary transport distance to the mill was 40 km. Additional information regarding the site and trees at time of harvesting is presented in Table 1.

TABLE 1: Harvesting Site Information per Average Stem.

Item of Interest	Measure	Unit
Volume/stem	0.29	m^3
Tonnes/stem	0.19	t
Mass : Volume conversion ratio	0.68	t/m^3
Free bole length	11.1	m
Maximum branch diameter	3.0	cm
Bark stripping length*	61.9	cm
Angle of branches to stem	40	degrees
State of majority of branches	Live	

* Bark stripping length is the measure of how far up the stem from the base of the tree the cambium and bark will rip-strip. This was tested infield immediately after felling by feller buncher.

5.1.1. Soil Compaction Susceptibility

The effect of soil compaction on tree and root growth in sandy soils such as those found around Kwambonambi is negligible from a long-term site productivity perspective (Greacen and Sands, 1980; Smith and du Toit, 2005). Smith *et al.* (1997) reported low compressibility indices for such soils. Very sandy soils (less than 4% clay) do not develop high levels of soil strength, even when compacted (Smith, 1998). Smith (1998) found no significant differences in stand basal area for soil compaction treatments in extraction routes between wheel ruts, adjacent to wheel ruts and furthest away from wheel ruts for *E. grandis*, *E. grandis* x *camaldulensis*, and *E. grandis* x *urophylla* in the Kwambonambi area. Vehicle traffic thus has no significant impact on future tree growth in the area from a soil compaction point of view. For this reason, potential adverse effects of harvesting traffic on the site were not included in this study

5.1.2. Reasons for Research Area and System Selection

The Zululand coast was the only area which employed multi-stem pulpwood harvesting systems in SA at the time of study. This can be attributed to these systems being well suited to the site conditions and the high timber volume required from the region. Concentration of these systems in this area led to the research area for the study being defined by default. At the time of project and research area definition, another multi-stem system was also available for study, but it had been recently implemented and was still in a start-up and operator learning phase. It was decided that a study of such a system would be of less value than of a system which had been operating for a longer period; more than one year in this case. The reason for this decision is that the more experienced system would already have a degree of structure, flow and basic operating practises establishment, and thus require a more scientific examination and research approach for potential improvement.

5.2. Harvesting and Transport System Selection and Study

This study focused on modelling a real world multi-stem forest harvesting operation (System 1) and two hypothetical multi-stem operations (Systems 2 and 3). All system models were created using Arena 9 commercial simulation software. The real world system represented by System 1 produced an average of 475.2 m^3 of pulpwood delivered to the mill per 11 h daytime shift during the period of study. The hypothetical System 2 makes use of exactly the same equipment as System 1, but differs in specific operating practise methods. This system was selected to assess whether or not simulation could lead to improved monthly production and/or reduced cost using identical equipment. System 3 is also a hypothetical system and differs partially in equipment type and function from Systems 1 and 2. It was selected to determine the potential of simulation in evaluating alternative resource options, as well as to determine if this system would be better suited to the required task and conditions than Systems 1 and 2.

5.2.1. System 1 – Current System

System 1 comprised the following equipment (see Appendix 1 for matrix):

Feller Buncher:	1 Tigercat 720D drive-to-tree wheeled feller buncher with continuous disc saw.
Grapple Skidder:	1 Tigercat 630C with dual arch bunching grapple.
Delimber-Debarkers:	1 Volvo EC 210BLC excavator with Maskiner SP650 head.
	1 Volvo EC 210BLC excavator with Maskiner SP551 head.
	1 Hitachi Zaxis 200 excavator with Maskiner SP650 head.
Slasher:	1 Volvo EC 210BLC excavator with Tigercat slasher deck.
Trucks:	3 Volvo FM400 6x4 rigid trucks with drawbar trailers.

Observed operation and interaction of the above-mentioned equipment in the real world operation was as follows: The feller buncher created full tree bunches infield for the skidder to extract. It did this by felling and dumping four (although occasionally it did more) head accumulations on top of one another per cycle. This was carried out by travelling in a straight line down a row of trees, either towards or away from the landing, felling and accumulating until the felling head was full. Once full, the machine dumped the accumulation (at an average angle of 70° to its direction of travel), and then reversed to the first tree in the adjacent (second) row. It repeated the head accumulation procedure in the second row and dumped these stems on top of the previously dumped stems, and once again reversed to the first tree in the following (third) row. This accumulation, dumping and reversing sequence was repeated until the final (usually fourth) row had been felled, accumulated and dumped. The machine then did not reverse, but began a new cycle again in the first row, travelling away from the bunch it had just created. In this manner it progressively moved towards and away from the landing (depending on its direction), turning when reaching the end of the compartment and repeating the cyclic process in the new direction. The machine was also responsible for opening up the (continuous) landing area adjacent to the roadside. Head accumulations created while opening the landing were not skidded (due to the extraction distance to the delimber-debarkers being zero). An average infield bunch presented to the skidder by the feller buncher was comprised of 36.6 stems. The compartment was 850 m wide, but maximum skidder extraction distance was 815 m due to the roadside landing taking up some of the compartment. The skidder extracted infield bunches butt-first to the landing, where the three delimber-debarkers delimbed, debarked and topped the stems individually. Once in tree length form, the slasher cross-cut the presented timber into 5.5 m pulpwood logs, dealing with several stems per cycle. It was also responsible for loading the pulpwood onto secondary transport vehicles, which transported the pulpwood from roadside to mill.

Added to timber extraction, the skidder had two additional tasks to fulfil, namely, returning of slash (produced by the delimber-debarkers) infield and indexing the tree lengths presented to the slasher by the delimber-debarkers. After each cycle the skidder operator would check whether or not there was sufficient build-up of slash at each delimber-debarker for a load. If there was, he would collect a grapple full of it and return it infield while travelling towards the following bunch to be extracted. Indexing of tree lengths at the landing involved aligning butt-ends using the skidder blade, making it easier for the slasher to cross-cut multiple stems into the required 5.5 m lengths. It was not practised often during the data collection period in this study (generally once per shift), but when it was carried out, all tree lengths on roadside were addressed.

The operation was hot, with established buffers usually lasting less than one day in the system before depletion if a machine went down. Shift length was 11 h, starting at 06:00 and ending at 17:00. Work was scheduled to take place for 10 of the 11 h. Scheduled breaks included breakfast from 09:00 to 09:30 and lunch from 12:00 to 12:30 for the feller buncher, skidder and delimber-debarkers. The slasher would take intermittent breaks between truck arrivals when required. In reality, the system ran day and night shifts. Due to accurate data collection only being possible during day shifts, however, the system was treated, modelled and cost as only working day shifts.

5.2.1.1. System Observation

The system was observed for a total of 191.1 h (11 468 min.) from 25th January 2007 to 28th February 2007. It was not observed every day, but when observed, it was usually for an entire shift. In each system observation, a single machine would be studied exclusively for a substantial period of time. This was done to reduce potential bias associated with only studying a machine at a specific time of day, as well as to reduce potential for the Hawthorne effect (a phenomenon in which an operator will increase/decrease in work rate when under observation). Cumulative machine observation periods are displayed in Table 2.

TABLE 2: Cumulative Observation Period per Equipment Unit.

EQUIPMENT	TIME OBSERVED (min.)	TIME OBSERVED (hr.)
Feller Buncher	1 181	19.7
Skidder	4 082	68.0
Delimber-Debarker #1	1 329	22.2
Delimber-Debarker #2	1 309	21.8
Delimber-Debarker #3	1 322	22.0
Slasher	2 244	37.4
TOTAL	**11 468**	**191.1**

Required observation time per machine was determined by cycle time and work element time variation (Appendix 2 shows the number of observations conducted per work element). Short cycle times meant increased observations per day, which is partly why the three delimber-debarkers were studied for a relatively short period (two full days each). Delimber-debarker and feller buncher work elements carried little variation between cycles, thus also contributing to their short observation periods. All observations resulted in collected data which exceeded the required amount to describe the respective means with a 95.45% level of confidence and a margin of error which was within 5% of the true mean. Formula 1 was used to calculate the number of observations required.

$$n = \left(\frac{40\sqrt{n' \sum x^2 - \left(\sum x\right)^2}}{\sum x} \right)^2 \qquad \text{(Formula 1)}$$

(extract from Kanawaty, 1992).

Where:

n = Sample size required for a 95.45% level of confidence and a margin of error of 5% of the true mean.

n' = Number of observations in the preliminary study.

$\sum$ = Sum of values.

x = Observation value.

5.2.1.2. Work Elements and Breakpoints

Work cycles were defined and divided into work elements, separated by breakpoints. Time consumption for a work element included all time elapsed from the start breakpoint to the finish breakpoint. Breakpoints used in the study were as follows:

Feller Buncher:

Bunch	Cut of first tree in head accumulation starts – Cut of last tree in head accumulation complete.
Dump	Cut of last tree in head accumulation complete – Last tree hits the ground.
Drive to tree	Last tree hits the ground – Cut of first tree in head accumulation starts.

Skidder:

Grapple load	Wheels of machine stop moving – Wheels of machine start moving after bunch has been grabbed.
Travel loaded	Wheels of machine start moving after bunch has been grabbed – Last stem hits the ground.
Collect slash	Last stem hits the ground – Machine starts driving with full slash load.
Travel with slash	Machine starts driving with full slash load – Last piece of slash hits the ground.
Travel unloaded	Last stem hits the ground (if slash not collected) – Wheels of machine stop moving.

Delimber-Debarkers:

Secure stem	Previous stem leaves delimber-debarker head – Roller wheels begin driving stem.
Delimb and debark	Roller wheels begin to driving stem – Stem leaves delimber-debarker head.

Slasher:

Fill slasher head	Last log hits stack/load – Cross-cutting bar activated.
Cross-cut	Cross-cutting bar activated – Cross-cutting bar goes through last stem.
Stack from cross-cut	Cross-cutting bar goes through last stem – Last log hits stack.
Load from cross-cut	Cross-cutting bar goes through last stem – Last log hits load.
Load from stack	Last log hits load (from previous cycle) – Last log hits load (from current cycle).

Added to the above-mentioned work element observations, moving times for the delimber-debarkers and slasher were also recorded. Moving time was measured from the instant that cyclic production stopped for machine movement (start break point) to the instant that cyclic production began after the machine had moved (finish break point). Downtime and other time consumptions for all machines were also measured from the instant that cyclic production stopped to the instant that cyclic production started again. Descriptions for these non-cyclic time consumption activities were noted.

5.2.1.3. Data Collection and Working

Accessories used during data collection included a stopwatch (set to centi-minutes), time study forms, a pencil and an eraser. Binoculars were also used while observing the skidder to overcome the problem of the 850 m distance between the roadside and the end of the compartment making accurate observation difficult. Flyback (snapback) timing was the time observation method used (Kanawaty, 1992). This method involves individual stopwatch observations per work element which are measured in isolation of other work elements (i.e. the stopwatch will begin each observation from zero elapsed time). Cumulative elapsed time was recalled at the end of every time study session and noted as well.

Truck data were obtained by combining arrival and departure times recorded at the harvesting operation with corresponding arrival and departure times recorded at the mill by the Mondi Business Paper weighbridge. Differences in times between departure from one point and arrival at the following point were calculated and included as truck travel time data.

Data were captured from time study forms into a spreadsheet software programme (Microsoft Excel). Following data capture, specific work element observation times were combined for some of the machines. This was done to produce observations for newly defined work elements (made up of two or more originally defined work elements) which were better suited for incorporation into the simulation model. All cyclic feller buncher work elements (bunch, dump and drive to tree) were consolidated into single observations per cycle. Distinctions of which row of trees the feller buncher had accumulated (i.e., first, second, third or fourth) in each of these new work elements were kept separate. Skidder data remained in the same format as had been collected and captured. The two delimber-debarker work elements (secure stem and delimb and debark) were combined to produce single cyclical observations for each delimber-debarker per operator. In the slasher data, one change was made, namely the combination of the “fill slasher head” and “cross-cut” work elements into a single work element. Once correctly arranged for simulation applications, the spreadsheet data were copied and pasted into text files in Notepad, from which they could be imported into Input Analyzer (a distribution-fitting programme compatible with Arena 9). Input Analyzer was used to fit the most appropriate theoretical distribution to each data set, respectively. These distributions were tested in terms of how well they described the data. The Kolmogorov-Smirnov (K-S) test was used for continuous distributions and the Chi-Square test was used for distributions describing integer data. Distributions with P-values of less than 0.05 were rejected, while distributions with P-values greater than 0.05 were not rejected. Of the 23 distributions fitted using Input Analyzer (one distribution was produced per work element data set), one was rejected. The rejected distribution (i.e., the number of stems per bunch presented to the skidder by the feller buncher) had returned a P-value of less than 0.05 following a Chi-Square test. An empirical distribution was therefore required to describe this data set. No normal distributions were used during the fitting of theoretical distributions to data, even if they had higher P-values than any of the other distribution options. The reason for this is that a normal distribution can result in the return of negative values during simulation runs from the function's tail (Kelton *et al.* 2003). Negative observations would be unrealistic in this situation, considering all real world observations were positive measurements (namely time, distance and number of stems per bunch observations). Formulas produced by Input Analyzer which were not rejected are displayed in Table 3.

TABLE 3: Input Analyzer Formulas

CATEGORY	UNITS	DISTRIBUTION	EXPRESSION	TEST	P-VALUE
FB: dist per cycle	tree rows	Beta	4.5 + 10 * BETA(5.28, 4.32)	χ^2	> 0.15
FB: head accumulation 1	minutes	Weibull	0.51 + WEIB(0.808, 3.62)	K-S	> 0.15
FB: head accumulation 2	minutes	Weibull	0.55 + WEIB(0.85, 3.83)	K-S	> 0.15
FB: head accumulation 3	minutes	Weibull	0.56 + WEIB(0.913, 3.94)	K-S	> 0.15
FB: head accumulation 4	minutes	Gamma	0.57 + GAMM(0.0774, 6.3)	K-S	> 0.15
FB: open landing (Step 1)	minutes	Weibull	0.67 + WEIB(1.1, 3.95)	K-S	> 0.15
FB: open landing (Step 2)	minutes	Weibull	0.67 + WEIB(1.04, 3.59)	K-S	> 0.15
FB open landing (Step 3)	minutes	Weibull	0.64 + WEIB(0.676, 3.75)	K-S	> 0.15
SKID: Grapple load	minutes	Lognormal	LOGN(0.83, 0.423)	K-S	0.052
SKID: collect slash	minutes	Lognormal	0.18 + LOGN(0.664, 0.339)	K-S	> 0.15
DDB1, Op1 cycle time	minutes	Erlang	0.2 + ERLA(0.0544, 9)	K-S	> 0.15
DDB1, Op2 cycle time	minutes	Lognormal	0.07 + LOGN(0.653, 0.204)	K-S	> 0.15
DDB2, Op3 cycle time	minutes	Erlang	0.13 + ERLA(0.0349, 13)	K-S	> 0.15
DDB2, Op4 cycle time	minutes	Lognormal	0.05 + LOGN(0.691, 0.247)	K-S	> 0.15
DDB3, Op5 cycle time	minutes	Erlang	0.07 + ERLA(0.122, 7)	K-S	> 0.15
DDB3, Op6 cycle time	minutes	Erlang	0.18 + ERLA(0.0712, 8)	K-S	> 0.15
SLASH: no index X-cut	minutes	Weibull	0.01 + WEIB(2.19, 2.73)	K-S	> 0.15
SLASH: index X-cut	minutes	Lognormal	LOGN(0.603, 0.197)	K-S	0.149
SLASH: load from X-cut	minutes	Lognormal	0.08 + LOGN(0.241, 0.105)	K-S	> 0.15
SLASH: load from stack	minutes	Lognormal	0.02 + LOGN(0.491, 0.163)	K-S	> 0.15
SLASH: stack from X-cut	minutes	Beta	BETA(9.45, 16.6664)	K-S	> 0.15
TRUCK: arrival rate	minutes	Weibull	11 + WEIB(67.5, 1.56)	K-S	> 0.15
Stems per bunch	# stems	EMPIRICAL	-	-	-

Formulas are expressed in the format used by Input Analyzer and Arena 9. "FB" refers to the feller buncher, "Skid" refers to the skidder, "DDB" refers to the respective delimber-debarkers and "Slash" refers to the slasher.

In Table 3, the formula for “FB: dist per cycle” is “4.5 + 10 * BETA(5.28, 4.32)”. This means it is a Beta distribution with $\beta = 5.28$ and $\alpha = 4.32$, shifted to the right by 4.5. Due to the data describing this distribution being made up of integers, however, this data set should theoretically have been modelled by a Poisson or a negative binomial distribution. This is because these distributions represent discrete units, whereas the Beta distribution is used for continuous modelling. The Beta distribution was used, however, due to the Poisson and negative binomial distributions both having P-values of less than 0.05 (leading to the distributions being rejected). The Beta distribution in describing the data returned a P-value of over 0.15, which would lead to far more accurate simulation as well as random number incorporation (which would not have been possible if an empirical distribution had been used).

Feller buncher head accumulations for rows 5 to 7 were uncommon, but did occur during data collection. The extensive observation period requirement per feller buncher head accumulation of this nature led to a small data pool for this application, which was insufficient for developing functions. During the 19.7 h cumulative observation period of the feller buncher, fifth row head accumulations were carried out 18 times, sixth row head accumulations were carried out eight times and seventh row head accumulation were carried out twice. These observations had to be included in the model, otherwise bias would have been introduced, but their data pool was insufficient and their impact on the system was minimal. As a result, averages of the observed cycle time values were taken as the values which would be used for these observations in the model at the frequencies observed in reality. It is for this reason that formulas for these work elements have not been included in Table 3.

Skidder average speed was calculated using recorded extraction time and distance data for the machine when travelling loaded, unloaded and with slash. These speed observations were plotted against the respective distances travelled. This allowed calibration of functions which described speed trend lines for each travel state per specified distance. Graphs for the respective travel speed curves can be found in Appendix 2. One should take note that these travel speed curves and observations include acceleration from stationary at takeoff and deceleration to stationary at the end of the work element. Short lead distances have larger acceleration and deceleration components than longer lead distances, which is why average travel speed increases at a decreasing rate in all the graphs as distance increases. The calibrated functions for the three travel states follow, along with the corresponding parameter statistics in Table 4:

Travelling loaded ($m.s^{-1}$): 0.579 + 0.181*Ln(dist) - 17.279*(1/dist)

Travelling with slash ($m.s^{-1}$): 0.003 + 0.404*Ln(dist) - 18.905*(1/dist)

Travelling unloaded ($m.s^{-1}$): -0.818 + 0.541*Ln(dist) + 2.511*(1/dist)

Where: dist = distance (m) from departure location to arrival location.

TABLE 4: Skidder Travel Speed Parameter Statistics

STATUS	SSE	TOTAL SS	SSReg	R^2
Travelling Loaded	15.32	31.55	16.23	0.51
Travelling With Slash	26.10	71.67	45.57	0.64
Travelling Unloaded	25.97	117.55	91.58	0.78

A 95% confidence interval was used for the estimated parameters.

Note should be taken that skidder productivity does not depend entirely on travel speed functions. The additional work elements in this study (grapple load and collect slash) also affect skidder cycle time, and their observation values are unaffected by extraction distance. Their contribution to the total cycle time thus effectively increases with decreased extraction distance due to travel time values decreasing. Productivity simulation therefore requires a combination of these work elements as well as travel speeds per extraction distance to generate cycle time observations.

5.2.1.4. Parameters and Assumptions

Time studies were conducted on the harvesting system for a period of slightly more than one month. This period may only represent a snapshot of the variation which the system could potentially manifest in different ways as conditions change over time. Factors such as new harvesting sites, varying weather conditions, season changes and different tree species and sizes could all potentially result in operation, production rate, cost and equipment balance shifts. This study assumed consistency of many of these variable conditions, based on the data collected within the specific period. This assumption would not have been acceptable if the system was to be accurately modelled over an extensive time period with changing conditions. Standardisation of some of the global variables as concluded by Law and Kelton (2000), however, did result in these variables not potentially confounding the study's results, and thus facilitated system modelling and improvement under controlled conditions for the required study period. Added to this, the specified time horizon for this study was operational (Section 2.1.1), meaning conditions were required to remain relatively consistent during the simulated study period.

Two delimber-debarker operators (Operators 2 and 3) both worked at an observed average work rate of 125% during the time studies. This Hawthorne effect had to be standardised to ensure that the simulated system would accurately represent reality when operators were not observed. Data thus had to be adjusted back to represent the operators at 100% work rate.

5.2.1.5. Simulation Model Construction Sequence

Once the time study data had been captured, simulation model construction was initiated. Steps in developing the simulation model were as follows:

1. Level of detail to be included in the construction of the model based on input data, model complexity and result requirements were defined. Simulation models should ideally be as simple as possible, provided there is no potential to compromise result integrity or real world system representation based on the model accuracy and outputs required (Law and Kelton, 2000). This principle is known as Ockham's Razor and was the approach taken in this study.
2. A simplified rough draft of how the flowchart model would be constructed (Appendix 3) was created. Important variables, attributes and equations required were also noted. The simplified flowchart and the simulation model produced from it needed to be similar in model logic and flow. Programme limitations and complexities surrounding the task of creating a model which represents reality within a simulation programme, however, often lead to the simulated model differing from the draft to an extent
3. A simplified simulation model was built off the flowchart model using Arena 9. Average values from observed data were used to describe time delays and other input variables required.
4. The simplified model was run several times. One of the purposes of this step was to crudely determine whether or not the proposed model would be adequate for the required simulation and return reasonable results. Since a simplified model was used, there was not as much risk of investing a substantial amount of time into an incorrect model. Corrections to the simplified Arena model were made according to the errors identified during and after the simulation runs. Adjustments were also made to ensure the model produced reasonable results and ran as required. The preliminary model did not need to be extremely accurate in terms of its output comparison with reality. It rather needed to provide a base from which it could be expanded into a model of higher detail and accuracy in Step 5 (Asikainen, 1995).
5. The simplified model was developed and extra detail included to produce a model which would imitate reality to the level which was required. Distribution expressions describing real world data were incorporated into the model logic to replace the average values used in step 3 as well. This was more of a process than a single step. It required several simulation runs, model adjustments, additions, subtractions and much model logic reworking and fine-tuning. Model verification and validation were continually

carried out in this step, and were often cyclical in conjunction with model adjustments and construction. Verification and validation are discussed in Section 5.2.1.7.

6. Animations were added to the model. These assisted in further model verification, as well as making the working model far easier to explain and present to external parties (Meimban *et al*. 1992).
7. Final verification and validation of the completed model were conducted to establish whether or not the model should be rejected. Once this step had been completed, the model was ready to be used for producing simulated observations, from which results could be drawn.

5.2.1.6. Simulation Model Logic and Flow

“Bunches” (full tree bunches produced by the feller buncher), “tree lengths” (produced by the delimber-debarkers) and “slasher bunches” (bunches of cross-cut pulpwood produced by the slasher) were the harvesting system commodity entities used in the simulation model. Changes between these entity types occurred at specified points within the model. Trucks were also treated as entities in the model. The reason for this was that they had to seize the slasher (at a higher priority than the tree length entities and the stacked slasher bunch entities also competing to seize the slasher) to be loaded with cross-cut pulpwood (slasher bunch entities) by the slasher.

Compartment and landing sizes had large influences on simulation model construction. As mentioned in Section 5.2.1, compartment width was 850 m. The landing was 70 m from roadside to the trees outside the landing area (Figure 10). The symbol “D” in Figure 10 represents the variable “cumulative dist” (i.e., distance from roadside). This variable was defined in the simulation model to monitor the feller buncher’s distance from the roadside.

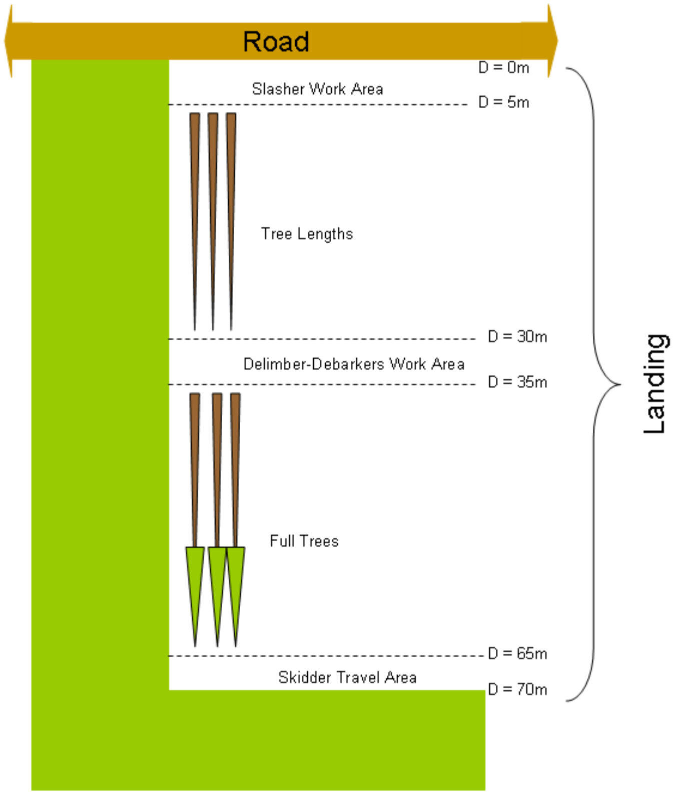

FIGURE 8: Landing Layout

Feller Buncher:

As mentioned in Section 5.2.1, the feller buncher was required to travel away from the landing, producing bunches as it went. It would then turn around at the end of the compartment and travel back to the landing, again producing bunches as it travelled. Upon arrival at the landing, it ceased its usual cyclic production and opened the landing before travelling away from the landing and producing infield bunches again. Opening the landing was done in three steps (Figure 11). Step 1 entailed felling eight trees per row from the 11th, 12th and 13th rows, parallel to the road. These felled trees were dumped alongside the standing rows, perpendicular to the road. Step 2 involved felling eight lines (perpendicular to the road) from the 14th row to the 23rd row. The feller buncher would fell one line of ten trees and then reverse back before dumping them on the site they had been standing. In Step 3, the feller buncher felled the remaining trees (row 1 to 10), once again taking eight lines perpendicular to the road. These trees were dumped on top of the trees felled in Step 2.

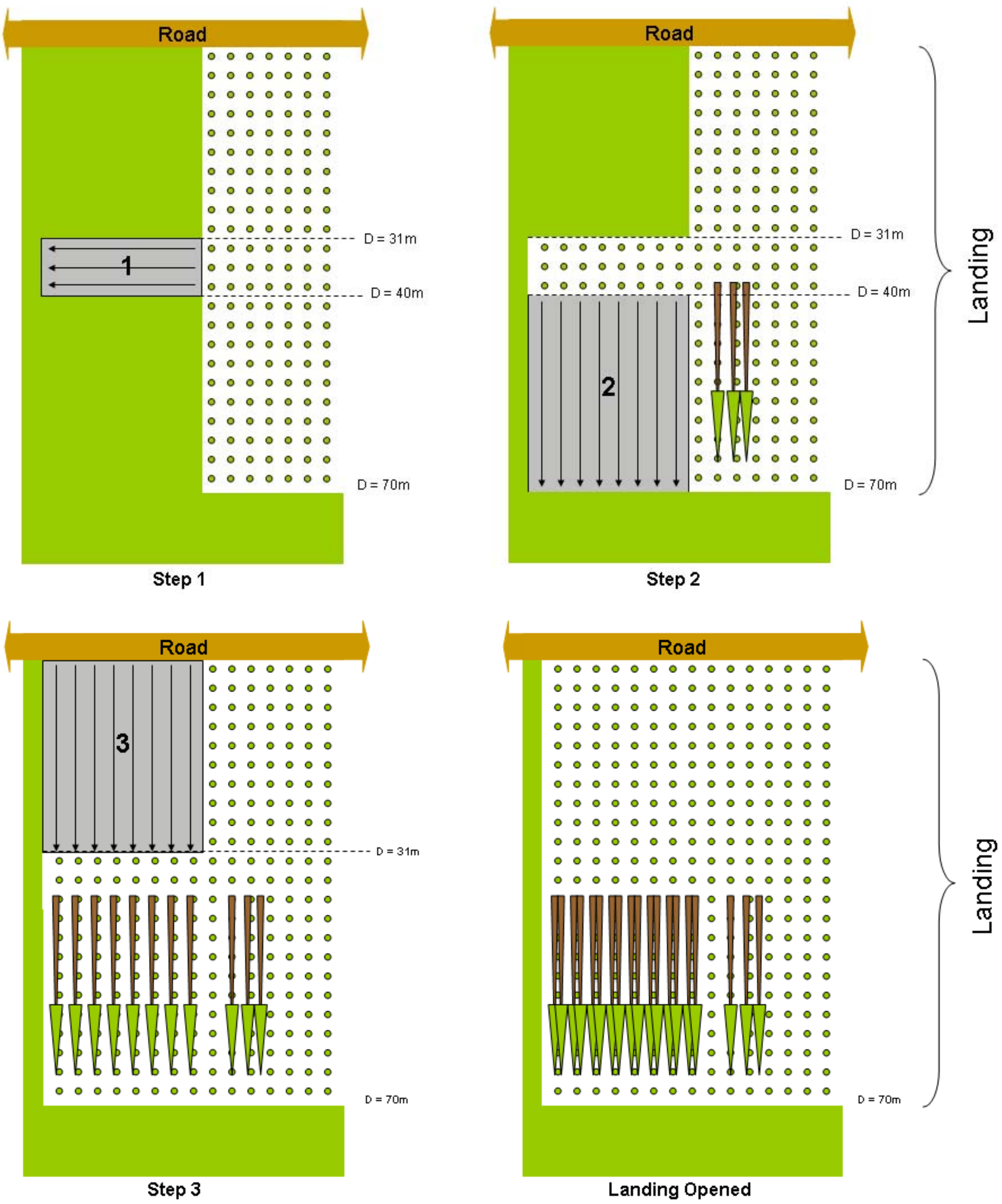

FIGURE 9: Feller Buncher Steps to Open Landing

Construction of model logic for ensuring the feller buncher turned around at the ends of the compartment required the inclusion of specific conditions which had to be met before the machine could change direction. "distance thresholds" (Figure 12) were variables used to set boundary felling distances (based on the compartment and landing sizes) after which the feller buncher should change direction. Distance thresholds set were 85 and 835 m from roadside respectively. A formula in a decide module would check every cycle if the feller buncher met one of these distance criteria (i.e., less than 85 m from roadside or more than 835 m from roadside) and whether or not it was travelling in the required direction, as well as ensuring the machine had not already turned around in the previous two cycles. If all these criteria were met, the feller buncher would turn around. The reason for the selection of the specific values for the distance thresholds had to do with the average distance the feller buncher would cover while producing a bunch (i.e., 30.0 m) and the required turnaround points' average values. The feller buncher needed to turn around at 850 m from roadside (the end of the compartment). For this reason, the feller buncher was instructed to turn anywhere after 835 m from roadside. With an average of 30 m/cycle, this meant that there was 15 m on either side of the 850 m turnaround point in which the skidder could turn on an average cycle (the grey "turnaround zone" area in Figure 12). Average turnaround distance would thus be 850 m, although each individual turnaround distance observation would be different. This was done because real world recorded turnaround cycles were incorporated in the bunching cycle data used in the model, but they were not separated from the rest of the bunching cycle data. This was to establish model simplicity to an extent, and because the turnaround cycle data were insufficient in isolation (due to few turnarounds being carried out by the feller buncher per day, leading to a small data pool after extensive study), but the rest of the bunching data was sufficient, even with the inclusion of the turnaround bunches. Model simplification entails simplifying the model where much logic and programming would be required in a situation which would not lead to a more accurate model. This was the case in this instance.

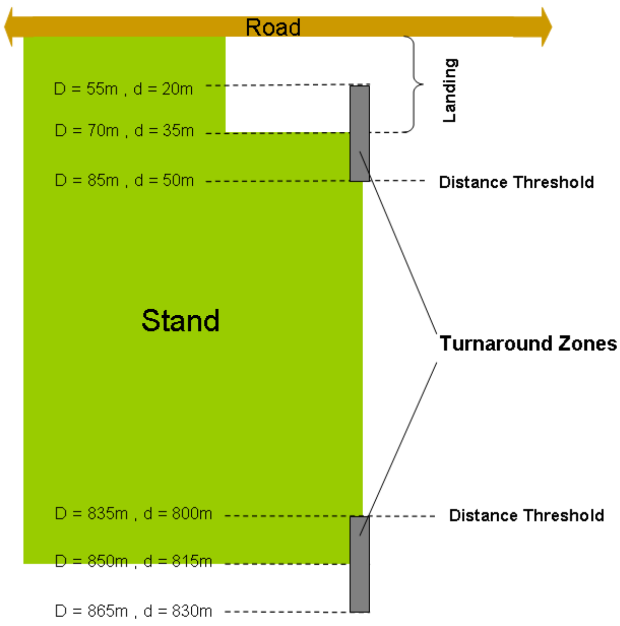

FIGURE 10: Feller Buncher Turnaround Thresholds and Zones

Figure 13 and Appendix 5 show the Arena 9 flowchart for the feller buncher portion of the simulation model. Each object is a flowchart module, with different shapes symbolising different applications. The model excludes all "ReadWrite" modules (used to record the observations produced by the entities as they pass through the flowchart modules) but includes all flowchart modules which influence the model's functioning. The small horizontal "T"-shaped symbols above some of the modules are used in model animation to represent queues. Entity movement occurs from the “bunch generation” module through to the two arrows on the right of the figure where entities leave the feller buncher portion of the model.

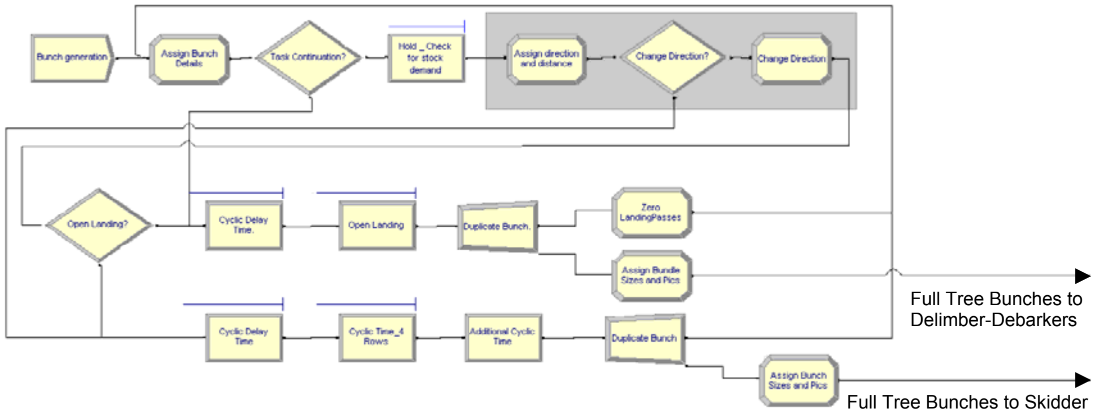

FIGURE 11: System 1 Feller Buncher Arena 9 Simulation Flowchart

At simulation run commencement, a bunch entity is generated in the “bunch generation” module. This is the only entity generated by this module for the entire simulation run. Other bunches are generated by duplicating this entity in duplicate modules and assigning different attributes to those duplications (thus differentiating each entity from the next). In the “assign bunch details” module, the entity is assigned, amongst other attributes, a “number of stems in bunch” attribute (a number describing how many full trees are in the bunch) and a “bunch distance from roadside” attribute (describing its distance from the roadside when it is dumped by the feller buncher). It also increases the value of a variable called “feller buncher cycles” by one. This variable quantifies the number of times an entity has gone through the cyclic feller buncher loop. The next module is a decide module which asks the question of whether the entity has passed through the feller buncher cycle at least once before. It does this by checking the “feller buncher cycles” variable. If this variable is equal to one, it means it is the first cycle in the simulation run (i.e., the feller buncher needs to open up the compartment, starting with the landing). In this case, the entity proceeds down to the “cyclic delay time.” module. From here, the entity will cause the feller buncher to open the landing (including any cyclic delay periods) and produce full tree bunches for the delimber-debarkers before looping back to the “assign bunch details” module. If the “feller buncher cycles” value is greater than one (meaning the compartment has been opened and machines are working in it), the entity proceeds directly to the “hold_check for stock demand” module. This module holds the entity (thus stopping feller buncher production) if there is no demand for stock from the rest of the system. Feller buncher stock demand is defined in the model by the amount of buffer stock available for the skidder and delimber-debarkers.

Distance and direction adjustments are carried out by the modules in the grey box in Figure 13. Feller buncher distance from roadside is monitored using a variable called “cumulative dist”. This variable is updated every cycle in the “assign direction and distance” module.

Another variable called "direction" indicates whether the feller buncher is travelling towards or away from the landing. It is initially defined as "+1", indicating that the feller buncher is travelling in a positive direction and gaining distance from the landing. This variable will become negative (indicating a direction of travel back toward the landing) when the feller buncher reaches the end of the compartment and has to turn around. Changing from a negative to a positive direction and *vice-versa* in the model logic is done by multiplying the feller buncher direction by "-1". The "change direction?" module checks after every bunch is produced by the feller buncher whether or not the feller buncher has reached a distance threshold. Changing direction is carried out in the "change direction" module. Another variable called "dist error check" increases by a value of one after every cycle and is zeroed when the feller buncher turns around. If it were not for this check, the feller buncher could end up getting stuck outside a distance threshold, and then simply change direction every cycle and never get anywhere. The value of this variable must be greater than three for the feller buncher to be able to change direction. If both the distance threshold and "dist error check" criteria are met, the feller buncher will turn around.

If the "change direction?" decide module calculates that the feller buncher needs not change direction, the entity proceeds to the "cyclic delay time" module in which the model determines according to a frequency distribution whether or not a cyclic delay period should be incurred, as well as the length of the delay period. If a cyclic delay is required, the feller buncher resource will be seized by the entity, delayed for the appropriate time period, and then released. The following module then seizes and delays the feller buncher for a time period equal to the time required to produce a bunch from four rows of trees. The next module, "additional cyclic time", asks the question of whether or not the feller buncher should be delayed to fell additional rows (the maximum observed number of rows felled to create a bunch in the real world operation was seven) as well as recalling duration values for accumulating and dumping those rows. The feller buncher is released by the entity after this module has been satisfied and the entity is duplicated (the original entity loops back to start the cycle again, and the duplicated entity is assigned attributes and moves on to compete for the skidder).

If the "change direction?" decide module calculates that the feller buncher does need to change direction, the direction is changed in the "change direction" assign module. The entity is then asked in the "open landing?" module whether or not the landing should be opened. The landing is opened after every second time that the feller buncher turns around (i.e., every time it is back at the landing). Answering the question of whether or not to open the landing is determined by a variable called "landing passes", which counts the number of times the feller buncher has turned around. It is increased by a value of one in the "change direction" module every time the feller buncher changes direction, and is zeroed in the "zero landing passes" module every time the feller buncher opens the landing. This means its value is zero when travelling away from the landing, one when travelling towards the landing and two when the feller buncher is about to open the landing. The "open landing?" module checks the value of the "landing passes" variable and if it is equal to two, the feller buncher opens the landing. If the value is less than two, it means the feller buncher has arrived at the turnaround zone at D >= 835 m and therefore needs to turn around and not open up the landing (as it is on the other side of the compartment from the landing). It therefore simply changes direction and continues cyclic production back towards the landing. Opening of the landing produces an equivalent amount of felled trees to the trees found in five bunches produced infield for the skidder. For this reason, opening the landing in the model leads to the duplication of five bunches of the original entity, which are then assigned different attributes and routed directly to the delimber-debarkers (as no primary transport is required) while the original entity loops back to start the feller buncher's flowchart cycle again.

Feller buncher distance from roadside after dumping a bunch is calibrated using the following formula:

$$\text{FB Distance from Roadside} = \text{Cumulative Dist} + (\text{Direction} \times \text{Bunch Dist})$$

Where:

FB Distance From Roadside	=	A variable describing the distance (m) the feller buncher will be from roadside after dumping the bunch of interest.
Cumulative Dist	=	A variable describing the distance (m) the feller buncher was from roadside after dumping the previous bunch (this value has to be updated after every cycle).
Direction	=	A variable describing the direction the feller buncher will be travelling while cutting the bunch of interest (+1 = away from landing landing; -1 = towards landing)
Bunch Dist	=	A variable describing the distance (m) the feller buncher will have to travel to create this bunch (taken from a distribution function)

Skidder:

Bunches from the feller buncher are the input entities for this section of the model. Infield bunches (outside the landing area) wait for the skidder at the "wait until skidder is free" module (Figure 14 and Appendix 4) in the order in which they were dumped by the feller buncher. Once the skidder resource is free, an entity can move through the following (assign) module in which it changes a variable called "skidder busy", which describes the skidder's state, from zero (meaning the skidder is free) to one (meaning the skidder is occupied). The first potential skidder delay period is found in the “cyclic delay time” module, in which the entity seizes the skidder, delays it for the appropriate amount of time if a cyclic delay is required, and then releases it. The entity then proceeds to the decision module regarding slash collection. During real world observation, the skidder collected slash from the delimber-debarkers for 85.6% of its infield trips. This decision module thus adheres to this, making the skidder collect slash on 85.6% of its trips. Following this decision, the skidder is then seized and delayed, either to travel infield empty or to collect slash and travel infield with slash. Skidder travel times per travelling condition (empty, with slash and loaded) were calculated according to the equations defined in Section 5.2.1.3. Once the entity has been extracted to the landing, it releases the skidder, changes the state of the “skidder busy” variable back to zero, and the entity moves on to compete for the delimber-debarkers, allowing the infield bunches to compete for the free skidder.

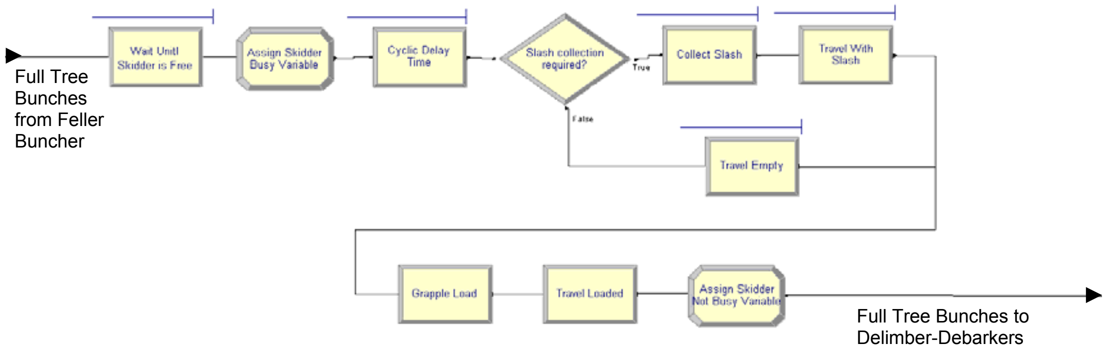

FIGURE 12: System 1 Skidder Arena 9 Simulation Flowchart

Delimber-Debarkers:

Once dumped at the landing, each bunch is assigned to a specific delimber-debarker. In reality, as in the model, a delimber-debarker will work through an entire bunch, one stem at a time, before beginning the following bunch. If all delimber-debarkers are busy, the bunch is assigned to the delimber-debarker with the shortest queue of stems. If one delimber-debarker is free and the other two are busy, the entity is assigned to the free resource. If more than one of the delimber-debarkers are free, resource selection for the entity is random between those delimber-debarkers (this eliminates utilisation bias). Random entity assignment if all three machines are free is carried out using the random number between zero and one which was assigned to the bunch in the feller buncher portion of the model. If the random number is less than $^1/_3$, the entity is assigned to Delimber-Debarker 1 (DDB1). If it is between $^1/_3$ and $^2/_3$, the entity is assigned to Delimber-Debarker 2 (DDB2). If it falls into neither of these categories, it is assigned to Delimber-Debarker 3 (DDB3). In the same way, if only two of the three delimber-debarkers are free, the entity undergoes random assignment but uses a value of $^1/_2$ as the cut-off (instead of the $^1/_3$ for 3 machines) to choose between the two machines. The "verification module" in Figure 15 (and Appendix 4) is simply used to error-check the model logic. If an entity does not meet any of the conditions in the "select delimber-debarker" module, it moves to the verification module, is recorded and disposed of. All entities should be assigned to one of the delimber-debarkers, and none should enter the verification module if the model logic is correct in this step. This was found to be the case when the model was run.

Following bunch assignment to a delimber-debarker, an entity change is required as delimber-debarkers deal with single stems per cycle. The bunch is split into a specific number of full tree entities by the "change bunches to stems" module (Figure 15) according to the assigned "number of stems in bunch" attribute which the bunch carried since the feller buncher section. Stems are then assigned individual attributes in the next module such as a new random number and entity picture. Stems are held until the delimber-debarker is free, following which the stem in front of the queue seizes and delays the machine before releasing it.

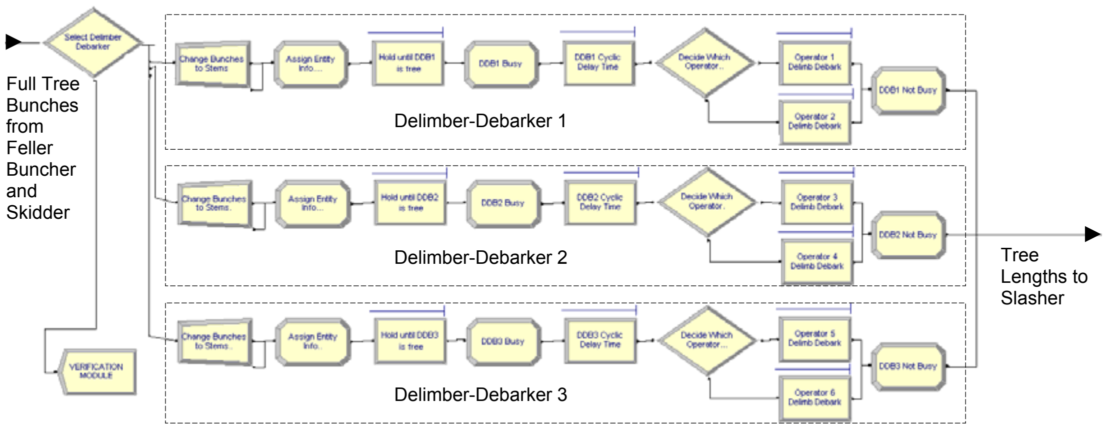

FIGURE 13: System 1 Delimber-Debarkers' Arena 9 Simulation Flowchart

During real world data collection, each delimber-debarker was observed with two different operators. Data for the respective pairs of operators could not be combined into single data sets due to the nature of the variation between operators' data. For this reason, two separate modules with different delimb, debark and top cycle times per operator were set up in parallel per delimber-debarker. The decide modules before the process modules define which operator production the entity will undergo, based on a probability percentage (which was calculated by comparing operator productivities to determine the entity production ratio between the two operators). Each probability percentage differs according to the nature of the relationship between the two data sets.

Delimber-debarker moving time from one bunch to another was treated as part of cyclic delay time because it led to a stop in cyclic production even though the machine was performing supportive work.

Slasher:

Slasher cross-cuts followed an erratic pattern in reality. The number of stems pulled into the slasher deck per cross-cut differed according to stem size, timber availability, truck requirements (a truck may have been close to fully loaded and required less than a full slasher's grab of pulpwood), stem taper (more stems could be cross-cut higher up the tree lengths due to decreasing diameter) as well as operator judgement. It was also affected by the operator including tree lengths which had not been cross-cut with those that had already had one or more pulpwood logs cross-cut off them. This was done to bulk up the amount of timber in the cross-cuts, thus overcoming to an extent the effect of tree taper on slasher payload per cross-cut. Breakdown of tree length entities into pulpwood log entities during slasher cross-cuts and subsequent assignment of the numbers of pulpwood logs and the types and sizes of the respective logs (the base log of a tree, for instance, would be larger than the logs higher up the tree) was decided to be an over-detailed approach to the issue of how much timber the slasher produced per cross-cut. It would also not be accurate, primarily because of the lack of any model's ability to simulate subjective human decision-making. As a result of this, the average amount of timber produced per cross-cut was used in the simulation model. It was calculated by dividing the total number of tree lengths cross-cut by the slasher during the real world observation period (i.e., 5 469 stems) by the number of cross-cuts carried out by the slasher on these stems (i.e., 720 cross-cuts). The average quantity of timber produced per cross-cut was calculated as being equal to the amount of timber found in 7.596 tree lengths (2.2 m^3). This was built into the model using the first five modules of the slasher simulation flowchart (Figure 16 and Appendix 4). Since tree length entities could not be split into decimal units, a decide module was inserted to make 59.6% of the tree length entities become slasher bunch entities made up of eight stems. The other 40.4% of the stems would become slasher bunch entities made up of seven stems. This ratio ensures that when the model is run, the average number of stems per slasher bunch entity will be 7.596. The two pairs of modules after the decide module batch the tree length entities into slasher bunch entities and then assign each new entity specific attributes such as a random number and a record of the number of stems making up the entity. The batch is defined as temporary, meaning it can later be separated back into tree length entities.

In reality, the slasher produced pulpwood logs which it either loaded directly onto a truck (if a truck was present) or stacked along the roadside (if a truck was not present). Once a truck arrived, the stacked pulpwood logs were loaded as first priority. If the stack became depleted before the truck was fully loaded, the slasher would begin to cross-cut tree lengths and load the cross-cut pulpwood directly onto the truck. Simulation of the slasher therefore required the inclusion of several conditions and options. It also had to work in conjunction with the trucks (keeping in mind the trucks had been defined as entities which also compete for the slasher). The “truck present?” module (Figure 16) is the first module that a slasher bunch entity will enter. The answer to this module (i.e., whether or not a truck is present) is decided by a global variable called “truck in system”. The value of this variable increases by one when a truck enters the system and decreases by one when the truck leaves the system. Thus if the value of this variable is greater than zero, it means there is at least one truck in the system and the entity will move to the “pulpwood to be loaded directly” assign module (indicating it should undergo cross-cutting and then be loaded directly onto the first truck). If the value of the variable is zero, the entity will be directed to the “pulpwood to be stacked” assign module (indicating it should undergo cross-cutting and then be stacked on roadside). Slasher bunches which are to be loaded directly from cross-cut are held to ensure that all previously cross-cut and stacked pulpwood is loaded onto the truck first. Once this condition is met or the truck has left the system, these entities are released. The following module, “truck still present?” establishes whether the entity was released because the truck left the system (in which case the entity loops back and starts the path again) or because the pulpwood is finished (in which case the entity moves on to be cross-cut and loaded directly onto the truck).

Whether slasher bunch entities are to be loaded or stacked, they still have to undergo cross-cutting. In the real world system, 42.8% of the cross-cuts carried out had tree lengths in them which had not undergone any cross-cuts in previous cycles. The remaining 57.2% only had tree lengths which had undergone one or more cross-cuts in previous cycles. There was a marked difference in work element times between these two alternatives (from collecting tree lengths through to the cross-cut itself), to the extent that their data could not be combined. This was because tree lengths which had not been cross-cut did not have accurately indexed bases, meaning the slasher spent more time aligning the butts before cross-cutting. Previously cross-cut stems were well indexed as they had been cross-cut in a straight cross-sectional line by the slasher’s chain and guide bar one or more cycles before. Because of this indexing situation, the “indexed butts?” module causes 42.8% of the slasher bunch entities in the model to be directed to the “cross-cut no index cycle time” module, in which each entity delays the slasher for a period which represents the slasher grabbing and cross-cutting tree lengths in which one or more stems have not been cross-cut in a previous cycle. The remaining 57.2% of the slasher bunches are routed to the “cross-cut indexed cycle” in which they delay the slasher for a period which represents all and cross-cut tree lengths having been cross-cut in a previous cycle. Cyclic delay time is dealt with in the module following the cross-cut modules and, like the delimber-debarkers, it includes the time incurred to move the slasher in the landing area, according to locations where the delimber-debarkers present the tree lengths.

Once the slasher bunch entity has undergone cross-cutting and cyclic delay, the model recalls whether the entity is to be stacked or loaded in the "stack or load?" module, as decided earlier in the "truck present?" module. If the timber was to be stacked, the entity enters the "stack from xcut" process module in which it delays and then releases the slasher. If a truck is then still not present, the entity runs through an assign module in which it increases a variable which monitors the pulpwood stack level by a value of one, and then waits in a hold module until a truck arrives. Alternatively, if a truck is present, the slasher bunch entity is diverted and becomes loaded on the truck.

If the "stack or load?" decide module found the entity was to be loaded directly onto a truck, the entity enters the "load from xcut" module and delays and releases the slasher before proceeding to another decide module. This next decide module also asks the question of whether or not a truck is still present. If a truck is still present, the entity increases the variable recording the number of slasher bunches loaded on the truck by one. The model then checks whether this slasher bunch is the final entity to fill the truck. If it is not the final entity, it is held in the "hold until truck is full" module until the model gives a signal to release this entity, along with the other slasher bunch entities loaded on the truck (and thus being held by this module). Alternatively, if a truck is no longer present, the entity is redirected and becomes part of the stacked pulpwood. It is held with the rest of the pulpwood until a truck arrives, at which point it will compete to be loaded by the slasher onto the truck, along with the other stacked entities.

It takes 25.635 slasher bunches to fill a truck to the average payload capacity of 55.6 m^3. In the truck section of the model, each truck is assigned an attribute which quantifies the number of slasher bunch entities required to fill that specific truck. Because slasher bunch entities cannot be split into decimals, the simulation model logic dictates that 36.5% of the trucks require 25 slasher bunches to fill them while the remaining 63.5% of the trucks require 26 slasher bunches. These ratios bring the overall value back to the required 25.365 slasher bunches per truck. Once the required 25 or 26 slasher bunches for the truck being loaded are met, a signal is fired by the model to release the truck from the roadside. The truck in then passes through a signal module, "signal_release loaded pulpwood" (Figure 17), which in turn fires a signal for the corresponding slasher bunches which were loaded on the truck, being held in the "hold until truck is full" module, to be released. The slasher bunches are subsequently un-batched back into tree lengths for recording purposes and tallied before joining the truck to be recorded and disposed of.

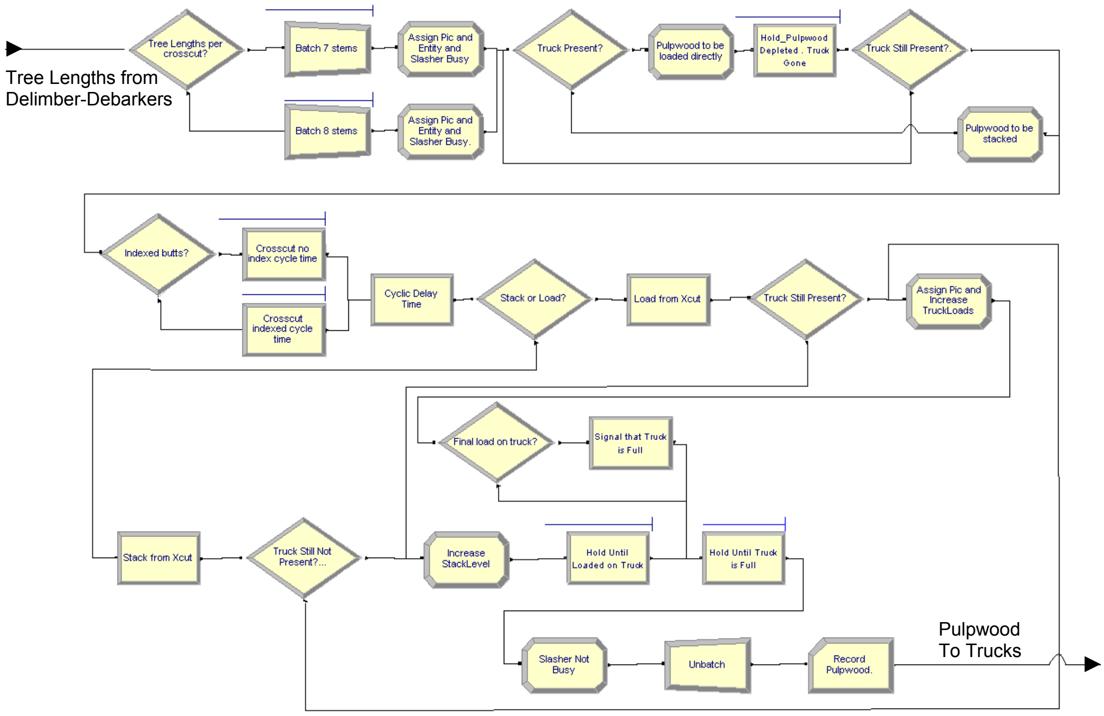

FIGURE 14: System 1 Slasher Arena 9 Simulation Flowchart

Truck Entities:

The truck section of the model is strongly dependent on the slasher section, and *vice-versa* in terms of variable assignments, attribute assignments and signals between modules allowing release of entities. Truck entities compete for the slasher at a higher priority than slasher bunch entities. As mentioned previously, if a truck is not present, a slasher bunch entity will seize the slasher, delay it for a cross-cut and stack period and then release the slasher and wait as part of the simulated roadside pulpwood stack. If a truck is present, this stacked entity will seize the slasher and delay it for the time period required to be loaded onto the truck. This process will continue with stacked pulpwood entities until the stack is depleted or the truck is fully loaded. If the stack is depleted before the truck is loaded, the truck releases the slasher, allowing tree length entities to seize and delay the slasher. In this case, however, entities are not cross-cut and stacked, but cross-cut and loaded directly onto the standing truck until it is fully loaded. Once full, the truck moves off, along with the timber which was loaded onto it.

Truck entities are created (Figure 17 and Appendix 4) at a rate which represents that of truck arrival at roadside in the real world system. Trucks are recorded and then enter an assign module in which they influence variables such as the number of trucks at roadside (this value is increased by a value of one for every truck that passes through this module) and assigned attributes such as their time of arrival. Trucks are then held to allow a maximum of only one truck interacting with the slasher at any given time. If no truck is interacting with the slasher and one or more trucks are waiting in the “hold_allow 1 truck at a time” module, one of these truck entities is released and assigned the number of slasher bunches required to fill it. Following this assignment, it reaches the decide module, “pulpwood present?”, in which the global variable responsible for recording the amount of cross-cut, stacked pulpwood is observed. If the value of this variable is zero, the truck entity moves to the “hold truck until loaded” module, where it waits to be loaded by the debarked tree lengths which seize the slasher, delay it while being cross-cut into pulpwood logs and loaded onto the truck and then release the slasher. Once the number of slasher bunches required for the truck have been satisfied, the truck is released. Alternatively, if the value of the pulpwood stack is greater than zero, the truck entity proceeds to seize, delay and release the slasher in the “load pulpwood” module. This module only accounts for a single slasher bunch being loaded onto the truck. Following this, the truck entity continues to the assign module where it increases the variable describing the number of slasher bunches on the truck by one and decreases the variable describing the number of slasher bunches in the pulpwood stack by one. It then causes a signal to be fired to the “hold until loaded on truck” module in Figure 16, releasing one slasher bunch. If this loaded slasher bunch was the final required bunch for the truck to be fully loaded, the truck entity would be released and signal the corresponding slasher bunch entities in the “hold until truck is full” (Figure 16) module to be released. These entities would subsequently remove themselves from roadside before being disposed of. However, if the loaded pulpwood slasher bunch was not the final required bunch, the truck entity loops back and begins the cycle again from the “pulpwood present?” module. The truck will remain in the system until fully loaded from stack and/or cross-cut, before being removed and disposed of along with the timber assigned to it in the form of slasher bunches (which, as mentioned previously, are split back into tree lengths and recorded before disposal).

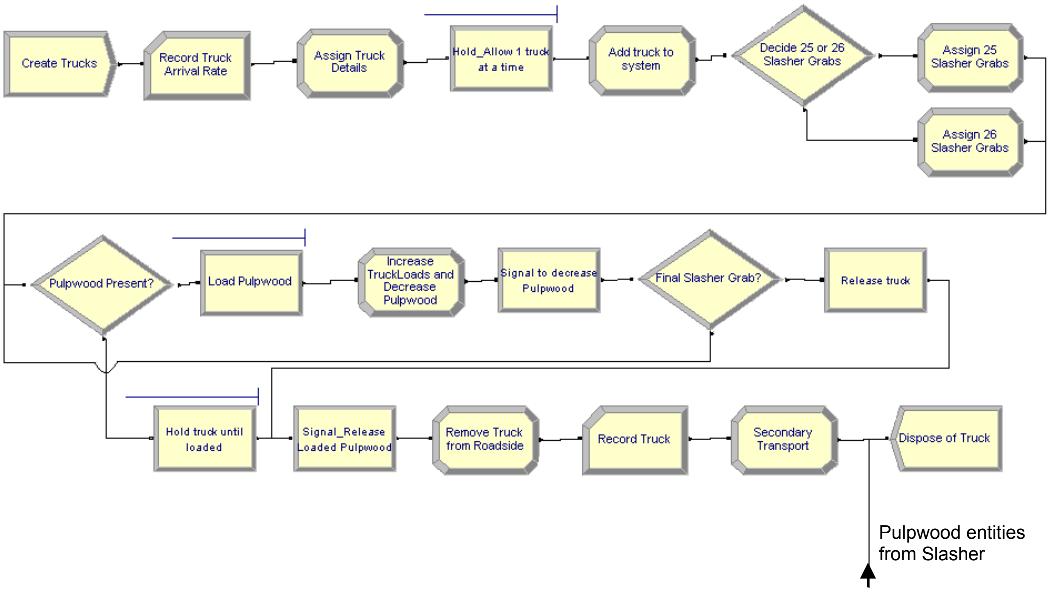

FIGURE 15: System 1 Trucks Arena 9 Simulation Flowchart

System Issues:

Downtime and other non-cyclic time-consuming activities observed during the data collection period were included per machine using continuous empirical distributions. Empirical distributions were used due to the erratic nature and time span of these delays per observation in the real world. Observed periods in which machines waited for stock in the real world system were not incorporated into any model logic, as these are reproduced by the model through entity and resource interaction dynamics (Kelton *et al.* 2003). Excluding flowchart model logic displayed and discussed in previous sections, the background data modules consisted of 36 variables, 46 queues, 29 export files, 21 expressions, four entity states, six resources, and two schedules.

Schedules were used in this study to define hours which were planned for resource work to take place. The first schedule, "machines with scheduled rests" was defined for machines which would stop operation for half an hour at 09:00 (for breakfast) and again for half an hour at 12:00 (for lunch). Machines to which this schedule was assigned were the feller buncher, skidder and delimber-debarkers. The second schedule, "machines without scheduled rests" was defined for machines which did not have scheduled rest periods during the day. This schedule was assigned to the slasher, which did not incur scheduled rests, but rather rested intermittently between truck arrivals as required.

Model setup parameters were defined as follows: The model was set to run for a simulated period of ten months (each month was a replication). Each month was made up of 26 working days, with one shift of 11 workplace hours per day. The reason for only simulating one shift per day was that data from the real world operation were only collected during the day shift, and thus to promote model accuracy, what was observed in reality is what was included in the model. Shifts and months were set to flow into one another, with the situation at the completion of one period being the situation at the start of the following period. Warm-up (transient) period for the model was comprised of one shift (i.e., 11 h). This warm-up phase was extremely short in relation to the length of time the model was run for. In reality, however, the system undergoes a brief warm-up phase when starting a new compartment, which had to be included in the simulation. The warm-up period defined was simply used to ensure that when measurement of the model was initiated, all equipment had some level of stock with which to work. Total running time for the model over the ten replications was 2 860 workplace time hours, from which the 11 h (warm-up period) were not included in the results, leaving a total of 2 849 h (170 940 min.) of observation time. These replication parameters were used for all other simulation models in this study apart from model runs used for verification, validation and truck comparison purposes, which differed only in number of replications.

5.2.1.7. Model Verification

Verification involves removing all anomalies and incoherent logic from the model. Model integrity was verified in this study using the verification techniques described in the paragraphs which follow:

Arena's built-in error report function automatically picked up certain anomalies within the model logic. Missing connectors, undefined variables and attributes, typing errors and inconsistencies were highlighted. The model would run until an entity reached one of these logic errors, at which point the entity would generate an error report message. These messages would state the location of the error and give a brief description of why the entity registered it as an error.

Arena's counters were used to monitor the state of the system during model runs. Counters displayed instantaneous values for specific model variables such as the number of entities within a defined section of the model (helpful in identifying blockages, hold-ups and other model logic errors), distance of feller buncher from the landing, direction of feller buncher travel (towards or away from the landing), stock buffer levels and timber delivered to the mill. This facilitated monitoring the system as a whole, as well as identifying model logic errors. A total of 17 counters were used to sift out model inaccuracies.

Arena's animation functionality was used for verification purposes. Basic animation within the flowchart itself (simulating entity movement, entity type and queue length) proved to be the most useful in this step. The reason for this was that it allowed the user to observe the model within the context in which it had been created (i.e., entities working within the flowchart, as opposed to observing an animation run which had been set up in isolation of the flowchart). Model run speed was set to a slow pace and individual entities were traced through the model. This allowed the user to identify incoherent entity behaviour (e.g., an entity selecting an incorrect path when passing through a “decide” module), which could then be addressed. Simulated queue lengths were used to identify entity blockages, hold-ups and abnormally short queues, which could then also be addressed.

The model was run for a simulated period of 11 440 h (686 400 min.) to ensure no traceable runtime errors were manifested from the given data within this time frame. A run of this length provides the user with a substantial amount of confidence in model logic robustness and acceptability due to the extensive pool of random observations incurred in this period without apparent model error.

5.2.1.8. Model Validation

Validation is the process of determining whether the model accurately represents real world conditions. Validation in this study was carried out using the system data used to build the model. This goes against recommendations by Reynolds *et al* (1981), who claimed that “Proper validation of a stochastic simulation model requires that the predictions of the model be compared with real world data that are independent of the data that were used in the construction of the model.” Lack of additional data due to this being the first multi-stem system study in the country meant this was not an option. This was not a critical problem in this study, however, as the model was specific to the particular system in the conditions studied and was not extrapolated to represent alternative operations or operating conditions. Validation methods used in this study are expounded in the paragraphs which follow:

Model output data were contrasted with the real world system’s observed outputs per work element. This approach assisted in ensuring that the model did not yield dissimilar results to reality on an individual activity basis. One unique issue regarding simulation model validation is that the modelled observation pool is often far larger than the observation pool it represents (i.e., the real world data) due to longer simulation run observations than real world observation. To overcome this problem, frequency distributions were generated for modelled and real world data. Modelled frequencies were then tested against real world frequencies using the Chi-Square test with the null hypothesis being that the simulated frequency distributions did not differ from the real world frequency distributions. Based on this test, none of the modelled frequency distributions were rejected when compared with reality as Chi-Square values were well below the allowable values, based on the respective degrees of freedom per distribution (Table 4). Graphs of the respective frequency distributions are displayed in Appendix 4.

TABLE 5: Chi-Square Test Results For Modelled Versus Real Frequency Distributions

Category	Chi Squared	DF	Allowable	Actions
FB: dist per cycle	0.2418	9	16.920	don't reject
FB cyclic time_4 rows*	0.2284	14	23.680	don't reject
FB: open landing_3 steps*	0.2592	14	23.68	don't reject
SKID: Grapple load	0.0299	8	15.510	don't reject
SKID: collect slash	0.0051	5	11.070	don't reject
DDB1, Op1 cycle time	0.0175	10	18.310	don't reject
DDB1, Op2 cycle time	0.0110	9	16.920	don't reject
DDB2, Op3 cycle time	0.0415	11	19.680	don't reject
DDB2, Op4 cycle time	0.0122	9	16.920	don't reject
DDB3, Op5 cycle time	0.0190	8	15.510	don't reject
DDB3, Op6 cycle time	0.0109	8	15.510	don't reject
SLASH: no index X-cut	0.0239	11	19.680	don't reject
SLASH: index X-cut	0.0307	7	14.070	don't reject
SLASH: load from X-cut	0.0132	9	16.920	don't reject
SLASH: load from stack	0.0184	9	16.920	don't reject
SLASH: stack from X-cut	0.1283	12	21.030	don't reject
TRUCK: arrival rate	0.0303	13	22.360	don't reject
Stems per bunch	0.0010	12	21.030	don't reject

* Feller buncher head accumulations for rows 1 to 4 and Feller buncher open landing steps 1 to 3 were each treated as respective work elements during validation. This allowed the combination between the various rows (in the case of head accumulations) and the combination between the steps (in the case of opening the landing) to be assessed for each, as well as ensuring individual value compliance.

Once all individual model activity times have been validated (Table 4), the issue to consider is whether or not resource interaction dynamic is adequately modelled (Kelton *et al.* 2003). This is done by comparing the modelled system's output/s (i.e., pulpwood and trucks) with the same output/s from the real world system. If the two differ significantly, it means the individual components (activities) of the model are working as required (see previous paragraph validation), but the way all those parts have been fitted together does not represent reality. To generate sufficient modelled data, the model was run for 40 simulated months (each month was treated as one replication). Simulated truck loads per month ranged from 210 to 232 over this period, with the average being 224.2. Considering only day-shifts, System 1 in reality produced 222.3 truck loads of timber in a 26-day month. A two-tailed t-test of paired means was run to determine whether or not there was significant difference between modelled and real world observations at a 95% confidence interval. The t-value calculated from this test at 78 degrees of freedom was 0.58. This was less than t(.05), which had a value of 2.00. The null hypothesis that there was no significant difference between the means at a 95% confidence interval was therefore not rejected. The range of truck loads into the mill per month can be attributed to model random number inputs and random observation generation leading to no two months producing the same results. Even a simulation model which "perfectly" reflects reality cannot be expected to produce identical results to the real system due to random number influence (Reynolds *et al*. 1981).

Resource capacities and entity rates were adjusted and outputs evaluated to ensure robustness of the model in terms of its logic and scope. Changes in inputs required changes in outputs, but a level of sanity was also required in the outputs (Asikainen, 1995). The model was not rejected based on this test either.

Traditionally in simulation studies, part of the validation process involved validating the random number stream to ensure no bias was being incorporated. This was done by running the model on different random number stream seed values and comparing the results. If results did not differ significantly from one another at a specified confidence interval, the model's random number stream would be deemed acceptable. A slight difference in outputs due to the random numbers producing random observations was expected, but not to the extent that the models would be deemed dissimilar. Part of the problem with random number generators is that they run in cycles if run for long enough periods. Arena's random number cycle length is 3.1×10^{57}, meaning it could run on an average personal computer for 2.78×10^{40} millennia before reaching it starting point again. Added to this, the random number stream initial value is changed after every replication in Arena to ensure unbiased, independent results as required by Baumgras *et al.* (1993). With the improvements in random number generators over time and the robustness of Arena commercial simulation software, therefore, random number stream validation was not necessary in this study.

5.2.2. System 2 – Modified System

As stated in Section 5.2, System 2 employs exactly the same units of equipment as System 1 (Appendix 1). It was constructed primarily to simulate potentially advantageous alterations to System 1's operating methods with the aim of improved equipment balance, productivity, production and cost. The alterations made to the system were as follows:

System-based changes:

- Fuelling and servicing (greasing and daily maintenance) of bottleneck equipment was carried out during scheduled working hours in System 1, but is now completed outside of working hours.
- Scheduled rest times were from 09:00 to 09:30 and 12:00 to 12:30, but these have been changed to 09:00 to 09:15; 12:00 to 12:30 and 14:30 to 14:45. The goal with this change was to break the 4.5 h afternoon session for the operators, leading to less fatigue and potentially better production.

Feller Buncher:

In System 1, the feller buncher was observed as being the least utilised unit of equipment within the system. For this reason, the aim was to utilise it more within the system to compensate for and thus carry some of the weight of the high utilisations of some of the other machines where possible.

- The feller buncher originally felled trees while travelling both towards and away from the landing, dumping head accumulations at an average of 70° to its travel direction. This led to accumulations sometimes being dumped on top of one another (bunches produced while travelling back to the landing would cover bunches produced while travelling away from the landing, and *vice-versa*). Added to this, bunches produced on the return trip to the landing were dumped at the average 70° to feller buncher travel direction, meaning they lay at 110° to the desired skidder extraction direction, leading to increased grapple and take-off times for the skidder. In System 2, the feller buncher only fells while travelling away from the landing, and travels back empty. This results in standardised bunch presentation for the skidder (all accumulations at roughly 70°) as well as bunches no longer being dumped on top of one another, all leading to faster grapple times for the skidder and accelerated timber supply for the delimber-debarkers (resulting in reduced bark adhesion).
- When obstacles which would hinder the skidder grappling a bunch were present in System 1 (such as humps, old stump piles, rocks and holes), head accumulations were simply dumped behind them, making the skidder incur unnecessary time in moving the obstacle or travelling around it. The feller buncher now travels beyond such obstacles before dumping.

Skidder:

- In System 1, if the skidder dropped a full tree from its grapple while travelling, it would continue its cyclic work and then, in the following cycle, stop with its grappled load above the stem. Once stopped, it would put down its entire load on top of the dropped stem and then attempt to pick up all the stems again. This often involved several failed grabs at the stems before the machine picked all the stems up and continued to travel towards the landing. A log recovery grapple is now mounted on the skidder's blade in an attempt to overcome the problem of stopping while travelling loaded. This grapple allows the operator to pick up stems dropped in the previous cycle without interfering with the load held by the grapple.
- Blade size has been increased (raised) by 50% of its original size, meaning less indexing cycles are required for the same amount of timber.
- Bunches were previously collected at both 0° (straight) and 90° to the skidder's take-off travel direction (the choice was defined by the skidder driver). All bunches are now collected at 90°. The reason for this is that the data from the real world System 1 showed that the average payload when collecting stems at 90° was 37.8 stems, whereas collecting stems at 0° had an average payload of 35.6 stems (a

difference of 2.2 stems, 6.09% and 0.62m^3/cycle). Average payload for the observed system was 36.6 stems, which included observations for collection of stems at 90° and 0°. Collecting at 90° would therefore result in a payload difference of 1.2 stems per cycle on average between System 1 and System 2. The increased payload came as a result of the speed (and thus momentum) the skidder could build up when collecting bunches at 90° before the full resistance of the trees was realised (du Plessis, 2007). This was possible as the full trees would sweep around behind the skidder during take-off, before aligning with the skidder to be pulled in the direction of skidder travel. Collecting bunches at 0° required the skidder to take off with no initial momentum and the full drag of the trees being experienced by the machine. The skidder operator would change from trying to take off with a bunch at 0° to taking off at 90° in the real world system if the bunch was too large to allow take off at 0°. Added to the increased payload benefit is also the fact that collecting at 90° allowed the skidder to settle the butts in the grapple before taking off by rocking the machine backwards and forwards after grappling the bunch. This reduced the potential for dropped stems by ensuring the grab was completely closed before taking off.

- The skidder did not index all tree lengths before they were cross-cut by the slasher in System 1. All these stems are now indexed before the slasher cross-cuts them, resulting in the slasher not having to move butts out of its path while travelling up and down the landing, as well as spending less time on butt alignment before cross-cutting.
- In System 1, the skidder would collect slash from any of the three delimber-debarkers. Now slash is only collected from the same delimber-debarker at which the skidder dumped the extracted bunch. This saves time which was spent travelling between delimber-debarkers at the landing.

Delimber-Debarkers:

- Time delay between felling and delimbing-debarking has been reduced by making the operation from the feller buncher to the delimber-debarkers hotter (see feller buncher and skidder points for how this has been accomplished). This leads to lower bark adhesion, meaning fewer passes over the stem by the delimber-debarker heads being required and thus faster throughput.
- A “first felled, first extracted” procedure is followed by the skidder in this system (made possible by the feller buncher only felling in one direction and thus not laying bunches on top of one another), leading to reduced bark adhesion and faster cycle times as well.

Slasher:

- System 1 had a small buffer between the delimber-debarkers and the slasher (generally lasting a few hours when utilised). This led to much slasher movement being required to acquire sufficient tree lengths for its cyclic activities. As slasher movement was difficult and slow (due to the slasher deck and hydraulic hoses' presence, as well as the cutting bar being powered by the same hydraulics as the tracks, meaning hydraulic tap shifts were required for every move), this was inefficient. A one-day buffer of tree lengths has been built in between the delimber-debarkers and the slasher. This will theoretically lead to less slasher movement, a more consistent timber flow for the slasher, and less risk of trucks not being loaded if a machine other than the slasher breaks down.

One of the major differences between System 1 and System 2 is the required entity waiting period between resources. The goal of this adjustment to the system was to reduce the amount of time between the tree being felled and the same tree being delimbed and debarked, but then to increase the amount of time between the delimbing-debarking activity and cross-cutting by the slasher (Figures 18 and 19).

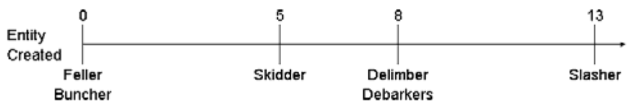

FIGURE 16: System 1 Cumulative Entity Waiting Period

FIGURE 17: System 2 Cumulative Entity Waiting Period

Data for System 2 were gathered using System 1's real world time study data. System 1's data were streamlined where required to include only observations which represented the required operating methods per activity or unit of equipment. Tests to ensure the streamlined data met the required sample sizes were carried out in the same manner as described for System 1 in Section 5.2.1.1. All tests revealed that the streamlined data exceeded the amount of data required to describe the respective means with a 95.45% level of confidence and a margin of error within 5% of the true mean. These data then followed the same process as the data used for System 1, described in Section 5.2.1.3, in which Input Analyzer was used to fit formulas to the respective data sets. Formulas were then used in the model logic for System 2. System 1's simulation model was used as a base in constructing System 2's model. The models' flowchart components were identical apart from the feller buncher section (Figure 20). Background model logic for the two models differed substantially though due to the dissimilarities in operating methods.

The feller buncher section of the flowchart model varied from that of System 1 because the feller buncher was now only felling in one direction (while travelling away from the landing) and returning without felling. An additional module, "return to landing", was added to model the feller buncher's non-felling return trip. Added to this, the model logic had to ensure the feller buncher only opened the landing every second time that it returned to the landing. This was because it was not felling in both directions of travel, meaning two runs through the compartment and return trips had to be completed for it to have felled the equivalent amount of infield stock as a single run and return in System 1. This was built into the logic in the modules within the grey box using additional variables and one new attribute.

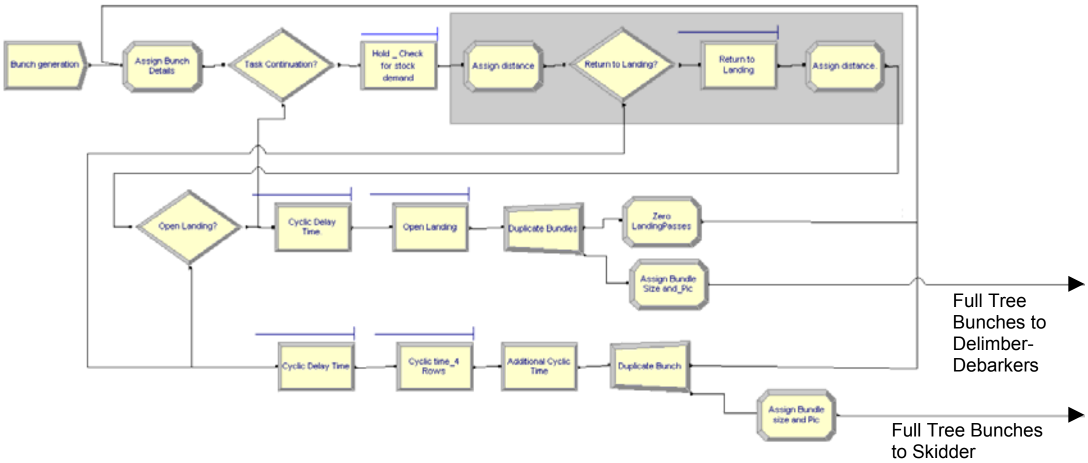

FIGURE 18: System 2 Feller Buncher Arena 9 Simulation Flowchart

One background logic point to note is that with timber being loaded a day later in System 2 than System 1, there are slightly more m^3 of timber per truckload in System 2 because of the timber being drier, and thus having decreased in mass by 1.9% due to moisture loss (Schonau, 1974). Trucks in the systems were mass-, not volume-restricted, so increased volume per truckload was possible. This meant that trucks had to be loaded with an average of 26.888 slasher bunch entities instead of the 25.365 slasher bunch entities in System 1 before releasing the slasher. To obtain this average value, 88.8% of the trucks required 27 slasher bunches and the remaining 11.2% required 26 slasher bunches. The slasher grapple was volume-restricted, resulting in it dealing with the same number of stems and m^3 per cross-cut, irrespective of timber moisture content, so its volume per cycle was not adjusted.

Verification and validation for System 2 followed parallel processes to System 1 (Sections 5.2.1.7 and 5.2.1.8) and similar outcomes were realised. One difference between the validation of this system and that of System 1, however, was that there were no real world data with which to compare the simulated observations. For this reason, the streamlined data taken from real world observation of System 1 (i.e., the effective real world inputs into System 2's model) were used to validate the model's outputs per activity in frequency distributions. As was the case with System 1, none of the modelled frequency distributions were rejected when compared with System 2's "real world" data (all Chi-Square values were well below the allowable values, based on the respective degrees of freedom).

Another validation issue incurred was that there was no way of comparing System 2's system-based outputs (i.e., timber quantity produced by the system per month) with any real world system outputs because the system did not exist in reality. As mentioned in Section 2.2.5.2, this situation prevails with all hypothetical models and requires desktop comparison between the model of interest and similar systems (if they exist) as well as analyst judgement (the analyst should be able to recognise any out-of-the-ordinary results). This was carried out and the model was deemed acceptable based on the results it produced versus expectation.

5.2.3. System 3 – Alternative System

System 3 is an alternative multi-stem system, differing from Systems 1 and 2 in terms of some of its resources (Appendix 1) and operating methods. It is made up of the following equipment:

Feller Buncher:	1 Tigercat 720D drive-to-tree wheeled feller buncher with continuous disc.
Grapple Skidder:	1 Tigercat 630C dual arch bunching grapple skidder.
Processors:	4 Volvo EC 210BLC excavators with Maskiner SP650 heads.
Loader:	1 Volvo EC 210BLC excavator with Rotobec grab.
Trucks:	3 Volvo FM400 6x4 rigid trucks with drawbar trailers.

The feller buncher and grapple skidder in this system operate in a similar manner to System 2. Subsequent to timber extraction by the skidder, four roadside processors delimb, debark and cross-cut the full trees to 5.5 m lengths. Following this, the cross-cut timber is loaded onto trucks by the loader and transported to the mill. Machine requirement for balancing combinations in this hypothetical system was first assigned by dividing the required system production rate by individual machine production rates to establish how many units were required per task. Refinements were then carried out in the simulation to ensure as far as possible that the system balanced within itself, as well as with the required production.

Data for this model were obtained in a similar manner to the data used in System 2 for the most part, namely through representative observations from System 1. This ensured as far as possible that the model would accurately represent its hypothetical real world system. Data for delimbing, debarking and cross-cutting with processors were collected from a real world operation, working in similar conditions to System 1, which made use of such processors. The model was constructed using System 2's model as a baseline. Flowchart logic was changed to accommodate the processors, loader and trucks operating within the system but feller buncher and skidder flowchart logic remained the same as that of

System 2. Background logic was changed extensively to accommodate System 3's requirements.

The Processor section of the module differed from Systems 1 and 2 in its setup (Figure 21). Four processors were modelled in the system instead of the three delimber-debarkers, meaning more flowchart modules were required to represent the fourth machine as well as extra background logic in the "Select Processor" module to ensure unbiased assignment of entities to processors. Another flowchart change was that the data used for the processors did not differentiate between different operators for each machine (as had been the case in Systems 1 and 2), meaning one process module per machine was required and the decide modules for which operator to select could be done away with.

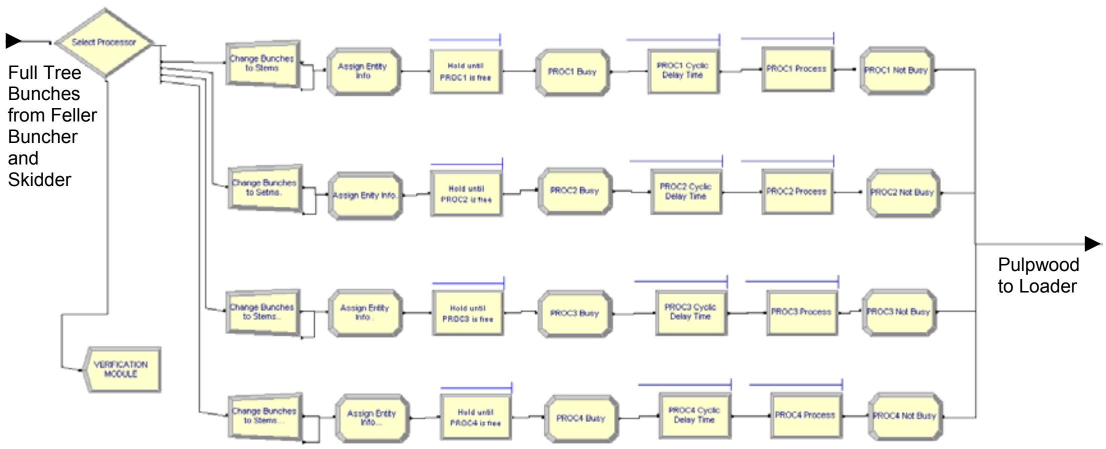

FIGURE 19: System 3 Processors Arena 9 Simulation Flowchart Model

System 3's loader flowchart and interaction with trucks differed from the slasher in Systems 1 and 2. This is due to the machine dealing only with one type of commodity entity (i.e., loader bunches, which were essentially the same entities as System 2's slasher bunches). Having one type of commodity entity flow through the loader's model simplified model construction for the loader and trucks as some flowchart contingencies, entity priorities and flow dependencies required for the slasher could be done away with (Figures 22 and 23). As was the case in System 2, delayed pulpwood loading was built into System 3's logic, meaning a requirement of 26.888 loader bunches per truck on average.

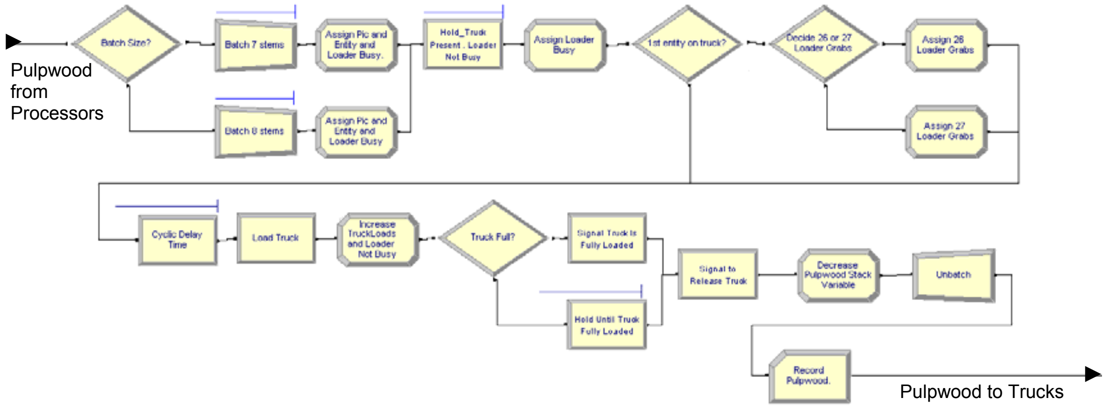

FIGURE 20: System 3 Loader Arena 9 Simulation Flowchart Model

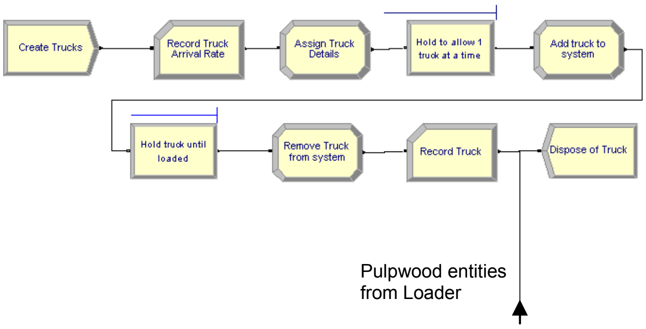

FIGURE 21: System 3 Trucks Arena 9 Simulation Flowchart Model

System 3 model verification and validation followed identical processes to System 2. As with System 2, no reason was found to reject the model or any activity within the model.

5.2.4. Additional Model Constructions

Once the three simulation models were completed, the addition of extra secondary transport capacity was required. The reason for this was that potential improvements in the harvesting section of the operation could potentially not be realised in terms of timber delivered to the mill because the trucks would bottleneck the system. This would lead to high roadside stocks, with little change in the number of entities recorded as leaving the model and being disposed of at the mill. Each simulation model therefore received an adjusted truck arrival rate to simulate four trucks within the system (instead of the original three trucks). Truck arrival data were obtained by speeding up observations for the original truck arrival rate data by 33.3%, thus effectively adding a fourth truck to the system. These models were run, verified and validated to ensure compliance with the other models.

5.2.5. Model Cost Calculations

All six simulation models (i.e., Systems 1, 2 and 3, each with three and four trucks respectively) were cost using standard cost inputs, internationally accepted cost calculation formulas (Appendix 5), results taken from simulation runs and working hours and days taken from simulation model parameters. This was done to compare system costs per m^3 of pulpwood produced. See Appendix 6 for an example of cost calculations carried out per equipment unit for System 1 with three trucks.

Cost calculations in this study did not include any overhead equipment, support personnel, support functions, support services, incentives, risk compensation or profit margin. Any add-on costs such as these would remain consistent in their composition and thus cost per unit time throughout all modelled systems. The only difference they would create would be in the value per m^3 of timber produced by the systems which were studied. Systems which produced more timber would carry lower overhead costs per unit of timber because the numerator (R/annum) would have remained the same, but the denominator (m^3/annum) would have increased.

Cost calculation assumptions made to ensure the cost conditions represented modelled conditions were as follows:

- All equipment units were scheduled to work 26 days/month (312 days/year).
- One shift was worked each day.
- Workplace time was 11 h/shift.
- Expected economic life (depreciation period) of all equipment was five years.

Capital cost per hour and unit timber for all systems could theoretically have been reduced by running the system for two or more shifts per day, rather than the one shift per day which was used in all cost calculations. This is because more hours and more timber would have been worked by the machines, leading to larger hour and timber volume numerators by which to divide the capital costs. Having said this, however, it is unlikely that all machines would have been able to sustain working more than one shift per day for the full five years. This is because many machine economic lives would have been surpassed in this period, leading to excessive downtime and high repair and maintenance costs. As a result, multiple shifts per day would lead to equipment being written off over a shorter calendaric period, thus increasing the fixed costs per day, month and year. The issue of the number of shifts per day did not have major bearing on the outcome of the study because its value was kept constant for all systems. This means that although the fixed cost figures would have changed based on changes in working parameters such as number of shifts per day, the ratios between the fixed costs from one system to the next would remain the same (provided all systems received identical changes to working parameters).

6. RESULTS AND DISCUSSION

6.1. Equipment Results and Comments

Simulated equipment output summaries in terms of time assignment, utilisation, productivity and cost are displayed in Tables 5 to 10. All times are expressed as percentages of hours scheduled for machine work (i.e., workplace time minus scheduled rest periods per machine). "Cyclic time" is the percentage of scheduled machine hours in which the machine carried out cyclic activities (i.e., value adding productive machine hours). "Supportive work time" includes all time in which non-cyclic work was carried out (e.g., skidder indexing tree lengths or a delimber-debarker moving to a new bunch of full trees). This time does not add value directly to any entity, but is vital for the functioning of the system (i.e., non-value adding productive machine hours). "Waiting time" is the sum of all time for which the machine could not work due to stock restrictions (either no stock was available for the machine or it had to stop production to wait for the rest of the system to catch up). "Other time" includes all observations which do not fit into any of the above time classification categories (Kelton *et al.* 2003). This includes time elements such as unscheduled breaks, fuelling, breakdowns and management intervention. Utilisation is a percentage measurement of the portion of scheduled machine hours in which the machine is actually used to perform the function for which it was purchased. In the case of this study, therefore, utilisation is calculated as the sum of cyclic time and supportive work time. Productivity per machine is quantified in m^3/PMH in these tables and cost per machine is expressed in R/m^3 of timber it produces.

TABLE 6: System 1 with Three Trucks Equipment Simulation Outputs

CATEGORY	FB	SKID	DDB1	DDB2	DDB3	SLASH
Cyclic Time	44.1%	66.9%	82.6%	68.4%	63.1%	53.3%
Supportive Work Time	11.7%	16.0%	2.7%	15.1%	12.8%	22.7%
Waiting Time	43.1%	-1.5%	1.9%	1.8%	1.9%	1.2%
Other Time	1.0%	18.5%	12.9%	14.7%	22.2%	22.8%
Utilisation	55.9%	83.0%	85.3%	83.5%	76.0%	76.0%
m^3/PMH	93.03	57.28	23.62	21.47	17.14	60.09
R/m^3	R 6.13	R 9.02	R 16.24	R 18.12	R 24.22	R 6.47

TABLE 7: System 1 with Four Trucks Equipment Simulation Outputs

CATEGORY	FB	SKID	DDB1	DDB2	DDB3	SLASH
Cyclic Time	44.0%	67.0%	82.3%	68.2%	63.6%	52.6%
Supportive Work Time	12.7%	17.5%	2.1%	15.8%	13.5%	22.4%
Waiting Time	43.0%	-1.9%	2.0%	1.6%	1.4%	2.3%
Other Time	0.3%	17.5%	13.6%	14.4%	21.5%	22.7%
Utilisation	56.8%	84.5%	84.4%	84.0%	77.1%	75.0%
m^3/PMH	91.29	56.42	23.75	21.30	17.04	60.97
R/m^3	R 6.18	R 9.05	R 16.26	R 18.19	R 24.12	R 6.43

TABLE 8: System 2 with Three Trucks Equipment Simulation Outputs (three trucks)

CATEGORY	FB	SKID	DDB1	DDB2	DDB3	SLASH
Cyclic Time	55.5%	76.3%	88.4%	88.2%	73.2%	58.0%
Supportive Work Time	16.0%	12.3%	1.5%	3.7%	9.1%	14.5%
Waiting Time	27.1%	-2.9%	3.1%	4.4%	1.9%	12.9%
Other Time	1.4%	14.2%	7.1%	3.6%	15.8%	14.6%
Utilisation	71.6%	88.7%	89.8%	91.9%	82.3%	72.5%
m^3/PMH	91.17	66.81	26.02	26.64	21.39	67.68
R/m^3	R 5.33	R 7.42	R 14.23	R 13.69	R 18.36	R 5.93

TABLE 9: System 2 with Four Trucks Equipment Simulation Outputs

CATEGORY	FB	SKID	DDB1	DDB2	DDB3	SLASH
Cyclic Time	56.2%	77.7%	88.3%	88.8%	74.4%	56.4%
Supportive Work Time	16.2%	11.7%	1.6%	3.8%	8.5%	17.8%
Waiting Time	26.2%	-3.0%	2.6%	3.8%	2.5%	7.9%
Other Time	1.4%	13.5%	7.5%	3.7%	14.7%	17.9%
Utilisation	72.4%	89.4%	89.8%	92.5%	82.8%	74.2%
m^3/PMH	91.45	67.31	25.97	26.59	21.63	80.49
R/m^3	R 5.28	R 7.33	R 14.25	R 13.65	R 18.08	R 4.91

TABLE 10: System 3 with Three Trucks Equipment Simulation Outputs

CATEGORY	FB	SKID	PROC1	PROC2	PROC3	PROC4	LOAD
Cyclic Time	55.4%	76.8%	89.5%	90.0%	77.1%	83.5%	18.8%
Supportive Work Time	15.8%	11.5%	1.6%	1.1%	8.2%	4.9%	10.0%
Waiting Time	27.5%	-1.5%	1.1%	1.5%	0.3%	2.6%	63.5%
Other Time	1.4%	13.2%	7.8%	7.4%	14.3%	9.1%	7.7%
Utilisation	71.1%	88.3%	91.1%	91.0%	85.4%	88.4%	28.9%
m^3/PMH	91.75	67.54	18.53	19.57	15.57	17.71	167.08
R/m^3	R 5.32	R 7.36	R 20.49	R 19.41	R 25.44	R 21.88	R 4.27

TABLE 11: System 3 with Four Trucks Equipment Simulation Outputs

CATEGORY	FB	SKID	PROC1	PROC2	PROC3	PROC4	LOAD
Cyclic Time	55.6%	76.9%	89.9%	90.0%	78.3%	83.2%	23.3%
Supportive Work Time	16.9%	11.3%	1.6%	1.1%	7.8%	5.0%	9.6%
Waiting Time	26.0%	-1.3%	0.7%	1.2%	0.4%	2.4%	55.2%
Other Time	1.5%	13.1%	7.7%	7.7%	13.5%	9.4%	11.9%
Utilisation	72.5%	88.2%	91.5%	91.1%	86.1%	88.2%	32.9%
m^3/PMH	90.17	67.50	18.55	19.56	15.65	17.66	181.13
R/m^3	R 5.35	R 7.37	R 20.42	R 19.42	R 25.17	R 21.96	R 3.54

One should take note at this point that utilisation and productivity should not be observed in isolation of one another. A machine may have a high utilisation for example, but due to a low productivity value as a result of poor operating practises, still produce a relatively small amount of timber each shift. Alternatively, a machine with a high productivity value which is under-utilised will also result in sub-optimal timber production per unit time. Another point to take note of is that the costs for the respective units of equipment cannot simply be totalled to obtain a harvesting cost for the system. The reason for this is that not all machines deal with all the timber moving through the system. The skidder does not work bunches which are produced when the feller buncher opens the landing and the delimber-debarkers (and processors in System 3) as well as the trucks are arranged in parallel, meaning the timber is divided between them. The system's cost of getting timber to the landing, for example, is less than the cost per unit of timber extracted by the skidder because the timber felled in the landing area does not require extraction and thus costs the system nothing. This brings system average extraction cost down. Timber felled in the landing area is not assigned to the skidder, however, meaning that based on the skidder's timber allocation (infield bunches only), extraction would be required for all timber assigned to it and thus lead to its extraction cost per unit of timber being higher than the system's extraction cost. In a similar manner, system delimbing and debarking (or processing in the case of System 3) cost is far less than the sum of all three delimber-debarker costs. System delimbing and debarking cost is made up of the costs from all three delimber-debarkers, but each of these costs is weighted in terms of its contribution to the system's total delimbed and debarked timber volume. The same is true for the trucks. Weighted equipment costs specific to each system operating as a unit are displayed in Table 11.

TABLE 12: Weighted System Costs (R/m^3)

Category	3 Trucks In System			4 Trucks In System		
	System 1	System 2	System 3	System 1	System 2	System 3
FB	R 6.13	R 5.33	R 5.32	R 6.18	R 5.28	R 5.35
SKID	R 8.27	R 6.81	R 6.75	R 8.31	R 6.72	R 6.76
DDB	R 18.92	R 15.13	-	R 18.95	R 15.06	-
SLASH	R 6.47	R 5.93	-	R 6.43	R 4.91	-
PROC	-	-	R 21.57	-	-	R 21.52
LOAD	-	-	R 4.27	-	-	R 3.54
TRUCKS	R 22.69	R 21.80	R 21.78	R 26.76	R 22.71	R 22.74
TOTAL	R 62.49	R 54.99	R 59.69	R 66.63	R 54.68	R 59.92

System 1 with three trucks is the benchmark model in Table 11 as it represents the real world operation. When compared with this system, System 1 with four trucks was more expensive by R4.14/m^3. For the harvesting section, it was only R0.07/m^3 more expensive, but in the transport section, the additional truck resulted in an increase of R4.07/m^3. This result highlights the fact that the inclusion of the fourth truck resulted in all trucks becoming under-utilised in this system, leading to the increase in cost. It can be deduced, therefore, that System 1 (and the real world system, due to the System 1 with three trucks model having been confirmed as an acceptable representation of the real world system) has the correct number of trucks serving it, specific to the harvesting system production.

System 2 with three trucks cost R7.50/m^3 less than System 1 with three trucks. Giving consideration to the fact that this system produced 508 m^3/shift of pulpwood, this equates to a saving of R3 811.43/shift for every shift that the system would work if the modelled standard could be maintained.

System 2 with four trucks, as with System 2 with three trucks, was an improvement on System 1 with three trucks. This system cost R7.81/m^3 less than System 1 with three trucks and R0.31/m^3 less than System 2 with three trucks. This was the cheapest of all the modelled systems. It produced 628 m^3/shift of pulpwood, meaning a saving of R4 908.27/shift from System 1 with three trucks.

System 3 with three trucks was more expensive than both System 2 models but was still cheaper than System 1 with three trucks by R2.80/m^3. Cost to delimb, debark, cross-cut and load onto trucks in System 2 with three trucks was R21.06/m^3, whereas in this system, the cost of the same activities using different equipment was R26.05/m^3 (a difference of R4.99/m^3).

System 3 with four trucks was cheaper than System 1 with three trucks by R2.57.m^3, but more expensive than System 2 with four trucks by R5.24/m^3. Since the feller buncher and the skidder portions of System 2 and System 3 models are identical and operate in the same manner, and the number of trucks in the systems are the same, the difference between System 2 and System 3 lies in the delimbing, debarking, cross-cutting and loading activities. The process of turning full trees at the landing into pulpwood loaded on a truck for System 2 with four trucks cost R19.97/m^3, whereas in System 3 with three trucks it cost R25.06/m^3 (a difference of R5.09/m^3). Based on this result, delimbing and debarking full trees into tree lengths at roadside with delimber-debarkers before cross-cutting and loading with a slasher can be classified within the study conditions as a more economically feasible option than delimbing, debarking and cross-cutting full trees into pulpwood with processors at the landing before loading with a loader.

6.2. Equipment Results Expounded

It is evident from the tables in Section 6.1 that some resources' utilisation values decrease with increased trucks in the system, which is the opposite of what was expected (more trucks should lead to less blockages and higher resource utilisations). In System 1, DDB1 decreased in utilisation by 0.9% from the model with three trucks to the model with four trucks. Slasher utilisation also decreased by 1.0% in this model. In System 3, skidder utilisation decreased by 0.1% and Proc4 utilisation decreased by 0.2%. None of the utilisation value differences were substantial though, and after analysis, it was discovered that they simply occurred as a result of the models performing as required and generating random observations, which by chance led to the results in the respective tables. One should also keep in mind when observing these values that non-cyclic supportive work time and delays all influence the utilisation figures. Non-cyclic observations within the models played bigger roles than cyclic activities in creating the variation between the utilisation figures. It is clear from Table 11 that the volume of timber produced per system increased in every instance when a fourth truck was introduced, as was expected.

In all simulated models, the debarking machines (i.e., delimber-debarkers and processors, respectively) were the bottlenecks. Two of the most important manipulations made during the system alterations from System 1 to Systems 2 and 3 were having less stock between the feller buncher and the debarking machines and adopting a first-in-first-out approach from the feller buncher to the debarking machines (as discussed in Section 5.2.2). Debarking resistance increases as timber and bark dry out (Grobbelaar and Manyuchi, 2000), meaning the moment of least debarking resistance in a harvesting operation under normal circumstances is the instant after the tree has been felled. Reduction of bark adhesion was the primary rationale behind reducing the amount of time between felling and debarking in Systems 2 and 3. Judging by the debarking productivity results obtained from these two systems in comparison with that of System 1, one can conclude that this adjustment resulted in the desired outcome being achieved. Debarking machines remained the bottlenecks in

Systems 2 and 3 even with the accelerated cycle times due to other machines within the systems having undergone productivity improvements. The issue of bark adhesion and its impact on the operation brings into question the potential suitability of a cut-to-length (CTL) system as opposed to multi-stem system in these conditions. One of the draw-cards of the CTL system relevant to bark adhesion is that debarking commences immediately after the tree has been felled, leading to low debarking resistance in comparison to full trees which are allowed to dry before being debarked.

As had been the case in the real world operation, the feller buncher resource in all modelled systems did not incur many “other time” observations. The reason for this was that the feller buncher was required to wait for the rest of the system for a relatively high percentage of time, meaning the operator took almost all his unscheduled rest breaks during this period. Fuelling, greasing and other basic functions regarding the machine were also generally carried out during these waiting times as required.

A smaller, cheaper, less productive feller buncher was considered for implementation in System 3 to improve system balance. Unfortunately, cycle time data were not available for such a machine and it was decided that manipulation of System 1’s data would potentially lead to inaccurate results and conclusions due to estimations having to be made regarding conversions for variables such as travel speeds, payload and non-cyclic time observations. Added to the lack of data, however, was also the understanding that the feller buncher was the cheapest machine in System 1 with three and four trucks, as well as System 2 with three trucks. It was the second cheapest machine in System 2’s model with four trucks and System 3’s models with three and four trucks. Possible cost savings to be realised from this resource on a system comparison level would therefore not be as potentially big as with other more expensive resources within the systems.

In all simulation model outputs, the skidder was recorded as having been monitored for working periods of over 100% of the time scheduled to it. Waiting time was calculated by Arena as 100% (the supposed total scheduled work hours) minus the observed worked hours, generating results which revealed negative waiting time periods. This problem occurred because the machine (like the other equipment units) would complete its last cycle before stopping work at the end of each shift (as is the case in reality). Given its long cycle times, however, this made up a larger overshoot of scheduled working hours than the other machines, leading to more than the scheduled work hours being recorded per shift and thus Arena’s assignment of negative values to waiting time. If, for example, at 17:00 the skidder had just begun a 10 min. cycle and a delimber-debarker had just begun a 30 s cycle, the skidder would end up finishing the cycle 10 min. later than its scheduled workplace hours, whereas the delimber-debarker would only work 30 s more than its scheduled machine hours to finish its cycle. These periods in which work was carried out in unscheduled working hours led to the excess of observation time in the model and thus the negative observations. True skidder waiting periods for these respective models are therefore not known, but it can be inferred that the values are small because the potential impact that the final cycles per shift could have had on the results generated within official shift hours is minimal.

It should be noted that the skidder average loaded speed when travelling a distance of between 250 and 800 m was fairly low, ranging between 1.5 $m \cdot s^{-1}$ and 1.8 $m \cdot s^{-1}$. Reduction in bunch size could potentially increase this travel speed and make the skidder more productive, even with the decrease in payload. This is an example of the different types of system questions that could be studied using the simulation system and further highlights the applicability of the simulation software for analysing forest harvesting operations. Since this goes beyond the scope of this study, it should be the focus of a future work.

When observing slasher and loader information in Tables 5 to 8 and Tables 9 and 10, respectively, it is important to keep in mind that neither of these machines had specified meal times. This means that in the time set aside for the other resources to not work, these machines were expected to be working by the model logic. As a result, operator rest periods for these resources fell into the “Other Time” and “Waiting Time” categories, which did not happen with the other machines. This accounts to an extent for the high non-cyclic time values and relatively low cyclic time values for these resources in each of the models.

In terms of trucks, high roadside stocks were observed in System 2 with three trucks and System 3 with three trucks. This was due to insufficient truck capacity in the system and the harvesting section of the system producing timber faster than the three trucks could remove it. System 1 with four trucks, on the other hand, had almost no observations for trucks being loaded from the cross-cut pulpwood stack. Timber was being cross-cut and loaded directly onto the trucks as the slasher and the rest of the harvesting system could not keep up with the truck arrival rate.

All costings in this thesis were specific to the studied conditions. Sensitivities of the costs to environmental cost drivers (such as tree size, bark adhesion and terrain) and economic cost drivers (such as capital costs, interest and fuel price) were therefore not incorporated. The impact of changes to these variables on the system could potentially result in alternative options becoming more or less feasible.

6.3. System Results and Comments

As mentioned in Section 5.2.1.8, System 1 in reality produced 222.3 truck loads of timber in a 26-day month. The modelled system differed from this output by 0.85%, simulating 224.2 truck loads to the mill on average.

Table 12 shows a system-based summary comparison of production and cost per system. All changes made to System 1 were found to be advantageous to a degree except for the addition of a fourth truck to System 1. System 2 with four trucks was found to be the cheapest option for getting timber to the mill. It showed a reduction in cost of R7.81/m^3 (12.5%), from R62.49/m^3 to R54.68/m^3. In terms of production increase, System 2 with four trucks was once again the most improved, taking production from 12 461 m^3/month (System 1 with three trucks) to 16 340 m^3/month – a 31.1% production increase using exactly the same harvesting equipment as System 1. Note that any comparisons of the numbers of trucks per month between systems in Table 12 should be carried out with the understanding that System 1's trucks were loaded with average payloads of 55.6 m^3, whereas System 2 and 3 had average payloads of 56.6 m^3 due to the timber being drier.

TABLE 13: Simulated System Production and Cost Comparison

Category	3 Trucks In System			4 Trucks In System		
	System 1	System 2	System 3	System 1	System 2	System 3
Trucks/month	224.2	233.3	233.6	225.2	288.5	287.8
m^3/month	12 461	13 213	13 230	12 517	16 340	16 300
R/m^3	R 62.49	R 54.99	R 59.69	R 66.63	R 54.68	R 59.92

6.4. Additional Tests and Results

Following on from the results discussed in the previous sections, certain theoretical adjustments to the simulation models were carried out to evaluate the effects of these changes on modelled system outputs. Delimber-debarkers and processors were the bottleneck machines for Systems 1, 2 and 3 respectively. This statement can be seen as a generalisation because these machines were connected in parallel, meaning that one operator may have had a far faster work rate than the others, but irrespective of his machine's work rate, his machine remained labelled as a bottleneck within the system because the other machines forced down the average production rate for that activity. To address this on a hypothetical level, data for the delimber-debarker operators were compared against one another to identify the operator with the fastest work rate, and likewise with the processor operators. Operator 3 (who worked on DDB2) was found to be the most productive of the delimber-debarker operators in System 1 and System 2, and Operator 2 (who worked on Proc2) was the most productive processor operator in System 3. What was then required was to change all functions describing operator work rates for the machines to the function describing the most productive operator in all six system simulation models. The models were then run and the results per model recorded (Tables 13 and 14).

TABLE 14: Additional Simulated Production Figures in Truck Loads per Month

Category	Current Truck Arrival Rate			Accelerated Truck Arrival Rate		
	System 1	System 2	System 3	System 1	System 2	System 3
Current Op.	224.2	233.3	233.6	225.2	288.5	287.8
Best Op.	223.9	233.1	234.1	226.1	292.4	289.7
Best Op, 2 Skidders					305.2	305.4
Best Op, 2 Skidders, 2 Slashers					309.2	

TABLE 15: Additional Simulated Production Figures in Pulpwood m^3/Month

Category	Current Truck Arrival Rate			Accelerated Truck Arrival Rate		
	System 1	System 2	System 3	System 1	System 2	System 3
Current Op.	12 461	13 213	13 230	12 517	16 340	16 300
Best Op.	12 444	13 202	13 259	12 567	16 560	16 407
Best Op, 2 Skidders					17 285	17 297
Best Op, 2 Skidders, 2 Slashers					17 512	

Production rate differences in Tables 13 and 14 between "Current Op." (i.e., current delimber-debarker or processor machine operator work rates) and "Best Op." (i.e., all delimber-debarker or processor operators working at the work rate of the most productive operator) systems were substantially lower than expected when considering the variation between operator productivities as observed in the real world data. The reason for this lack of substantial production rate increase (and in some systems, lack of increase at all) was due to a shift in the assignment of the bottleneck equipment in each system. All systems which made use of three trucks were now limited by the truck arrival rate. Systems making use of four trucks were also limited due to a shift in bottleneck equipment, but this limitation came from the skidder. System 1 was more hindered than Systems 2 and 3 due to its skidder having been more closely balanced with its delimber-debarkers.

At this point, it was decided that no model with three trucks was worth pursuing further changes with due to the trucks being the limiting factor, thus nullifying the effects of any potentially beneficial changes as identical models with four trucks already existed. System 1 with four trucks was also not pursued further due to any potential increases in the production of this system still being far removed from those of Systems 2 and 3.

The problem of the skidder being the bottleneck in Systems 2 and 3 was addressed by increasing the skidder's capacity from a value of one to a value of two in both these models, thus effectively creating another skidder. Once this adjustment had been made, it was found that System 3's monthly production was slightly higher than that of System 2. This was because the slasher in System 2 was now the bottleneck, whereas System 3 did not make use of a slasher. Slasher capacity was doubled like the skidder's capacity had been, to produce a new production value for System 2 (Tables 13 and 14). This process could have continued indefinitely as bottleneck volumes for machines are exposed with every capacity increase. System 2 and System 3 at this point had production figures of 17 512 m^3 and 17 297m^3/month respectively. Bottleneck machine for both systems was the feller buncher. Bringing in additional equipment, however, leads to new system balance, utilisation and cost figures. Additional delimber-debarkers were not added because their individual capacities had been increased through simulated improved operators. The simulated improvement led to them not bottlenecking the system (essentially having the same effect as adding another delimber-debarker, but far cheaper). If this avenue of simulated production increase through the requirement of additional equipment capacity was to be explored, costs would have to be re-calculated at every step. This falls outside of the scope of this study as the objective was to increase system production through adjusted operating practises and equipment configurations rather than through resource addition.

No change in truck transport distance to the mill was observed during the data collection period. This came as a result of the harvested compartments standing adjacent to one another and sharing a common road. Trucks in a circular loop on the forest road past all the compartments, meaning the transport distance to the mill was exactly the same for all studied compartments. It is important to note here that this condition was specific to the conditions studied during data collection. It is clear from Table 13 that truck balancing with harvesting system production is vital for production efficiency and cost. Changing transport distances would mean re-balancing would be required as truck productivity would be affected.

7. CONCLUSIONS AND RECOMMENDATIONS

Objectives of this study were to:

1. Determine whether or not commercial simulation software can be used to adequately model forest harvesting operations.
2. Gauge potential system balance, production and/or cost improvement/s achievable through application of simulation-based operation adjustments.
3. Define beneficial equipment operation and application practises for multi-stem systems.
4. Through construction and use of the commercial software package in producing forest harvesting operation models, evaluate the software's usability in terms of its applicability to and ease of use in such operation models, as well as its ability to meet forestry-based user requirements.

Outcomes of the study, based on the objectives listed above, were as follows:

1. System 1 with three trucks was the simulation model constructed to represent the real world multi-stem system using Arena 9 commercial simulation software. It acceptably represented reality on every level, from individual work element times to machine interaction dynamics and overall system production. The final outcome on a system level was that the real world and the model differed by an average of 0.85% in overall production. Conclusion is that commercial simulation software can be used in forest harvesting operation applications to adequately simulate reality.
2. System balance was improved most noticeably in the decrease of feller buncher waiting time from 43.1% of its total scheduled work hours (System 1 with three trucks) to 26.2% (System 2 with four trucks), thus normalising to an extent the system utilisation. Production improvements were clearly evident with simulated timber over the weighbridge per month being increased by 31.1% from 12 461 m^3/month in System 1 with three trucks to 16 340 m^3/month in System 2 with four trucks. Cost reduction was also realised, with the cost per unit of timber decreasing by 12.5% from R62.49/m^3 in System 1 with three trucks to R54.68/m^3 in System 2 with four trucks.
3. Several beneficial operation and application practises were identified in System 2, which led to the successes mentioned in point 2 (above). Not all changes made in this study, however, would necessarily produce the same positive result in other multi-stem operations. Improvements were gauged according to the studied harvesting operation under specific conditions. Applicability of these operation adjustments to improved operation in other systems would therefore be expected to vary to an extent with system configurations and operating environment. Some of the more significant practises identified were as follows:

- Fuelling and greasing bottleneck equipment outside of scheduled work hours.
- Providing operators with more, shorter scheduled rest periods.
- Feller buncher presentation of bunches for the skidder needed to be consistent and clear of obstacles.
- Skidder log recovery grapple mounted on the skidder blade for collecting stems dropped in previous cycles.
- Skidder collection of bunches at an angle of 90° to its takeoff direction
- Minimal time delay between felling and debarking required for reduced bark adhesion.
- Larger stock buffer between the delimber-debarkers and the slasher, meaning less slasher movement, less skidder indexing cycles, higher slasher productivity and increased volume payloads per truck.
- Implementing the correct number of trucks to balance with the harvesting system.

4. Commercial simulation software usability in forest harvesting operation modelling was found acceptable in some parts and difficult to work with in other parts. Some of the more prominent points regarding this include:
   - The software requires a fairly qualified level of user expertise due to the complexities associated with forestry operations, which lead to the user inevitably having to use more advanced aspects and functionalities of the software.
   - Extensive variability of forestry operations led to model logic construction proving to be an involved, complex process which carried many inter-dependencies between logic components in this study. Numerous attributes, conditions, assignments, variables and expressions were required as a result, making adjustments to model logic a substantial task.
   - Input fields and output reports were not always in formats which proved to make much sense or be much use for interpretation into a forestry context.
   - Simulating and tracking resource and entity movements within a stand requires much model logic and error checks.
   - Built-in user aids such as error checks and extensive help functionality make the programme easier to work with.
   - Software interface layout is user friendly and easy to work with.
   - Module flowchart construction is made simple by the “drag and drop” modules which can be opened and closed for logic inclusion as required.
   - Once constructed, models were found to be easily adjustable on the flowchart level. Any changes in background logic, however, were more difficult.
   - Use of Input Analyzer made data incorporation into the model an easy task.
   - The software is capable of handling heavy simulation runs with numerous entities for extremely long periods of time.
   - The software was found to be reliable and robust.

Acceptable models were produced using the commercial simulation software, meaning it has a framework which can be used for the construction and simulation of forest harvesting operations. The software was clearly not designed for forestry applications per se, but it can be manipulated into providing the required results in usable format based on specific inputs.

A recommendation for future simulation study would be to collect CTL time study data and simulate a CTL system. Simulated comparison between CTL and multi-stem systems could be explored, as well as potential improvements to the CTL system. Another potential future study line is the effect of changes in bunch sizes produced by the feller buncher on skidder and system productivity and cost.

The process of operation abstraction and simulation has been confirmed as being acceptable by this study, as with other studies carried out internationally. Potential for improvement of operational models has also been confirmed by this study amongst others. A point of further study now waits in the form of applying the improved system scenario into reality and monitoring the outcomes. This requires implementing simulated adjustments (the changes made to System 2 with four trucks in this case) into the real world system and running further time studies to evaluate how accurately the model forecasted reality.

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APPENDIX 1: Simulated System Matrices

Activity \ Location	Stand	Roadside	Mill
Fell and Bunch			
Skid			
Delimb, Debark and Top		**3X** 	
Cross-Cut and Load			
Transport			

Systems 1 and 2 Matrix

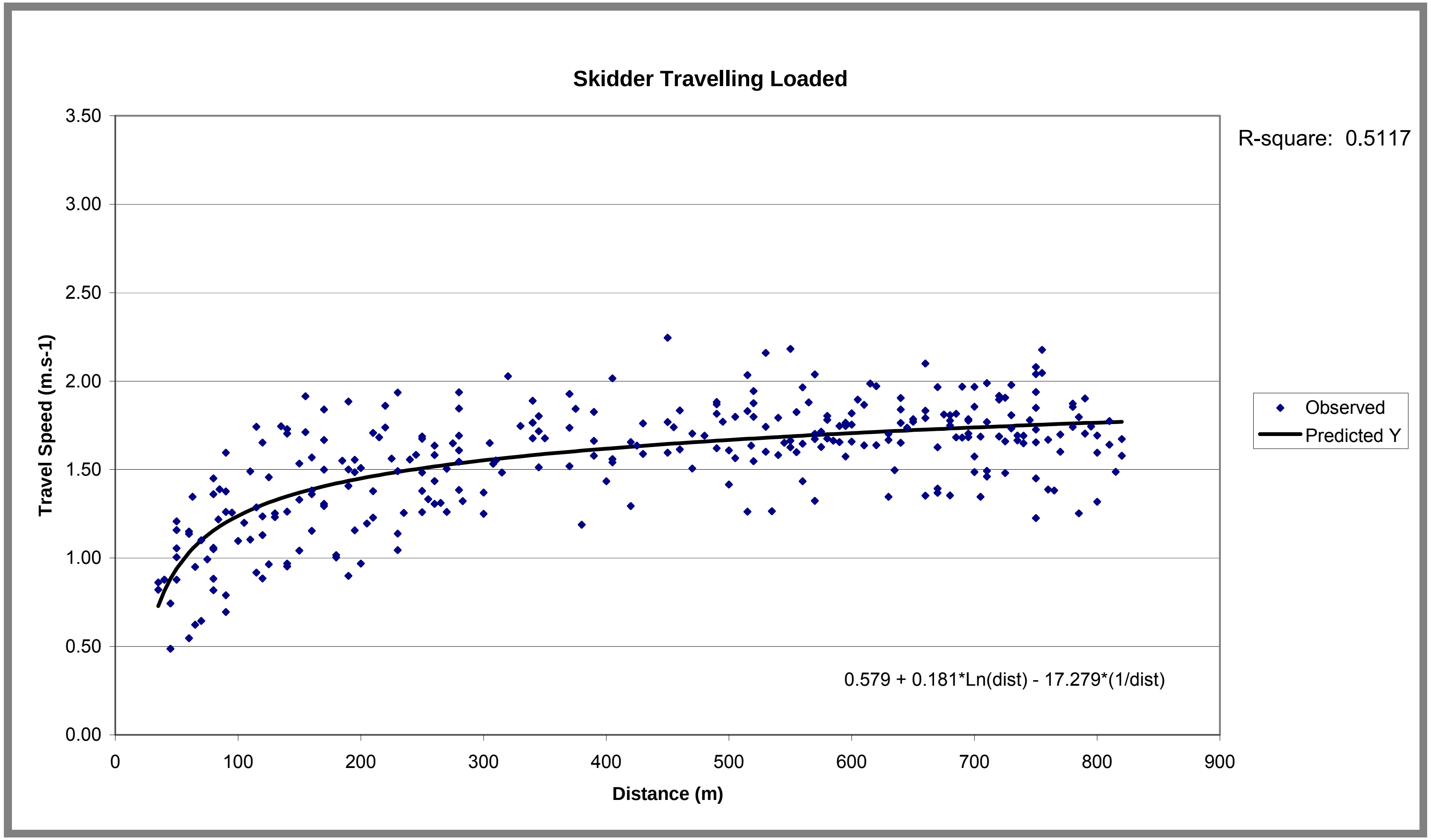
Location / Activity	Stand	Roadside	Mill
Fell and Bunch			
Skid			
Delimb, Debark and Cross-Cut		**4X** 	
Load			
Transport			

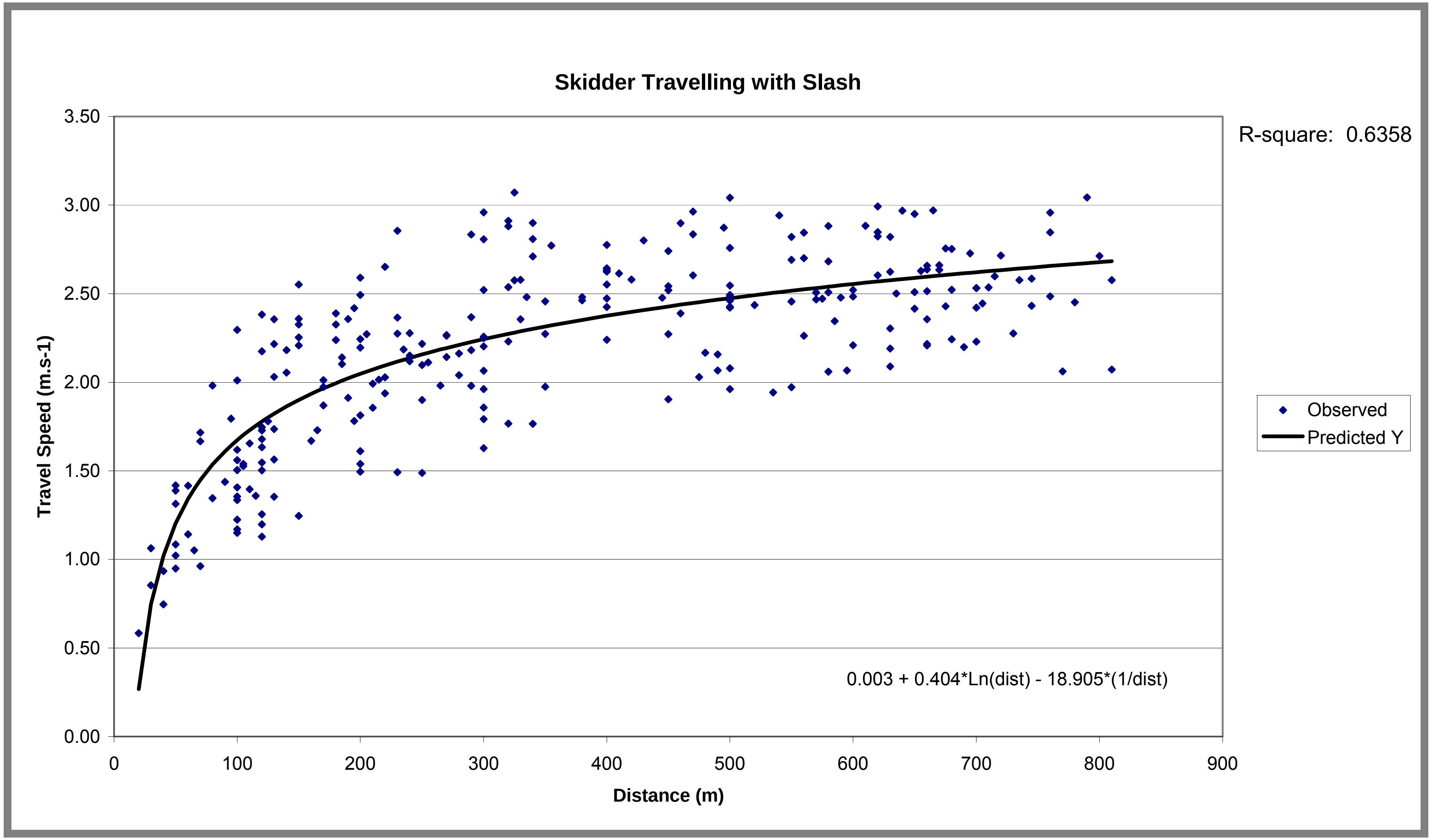
System 3 Matrix

APPENDIX 2: Data Collection Observations per Work Element

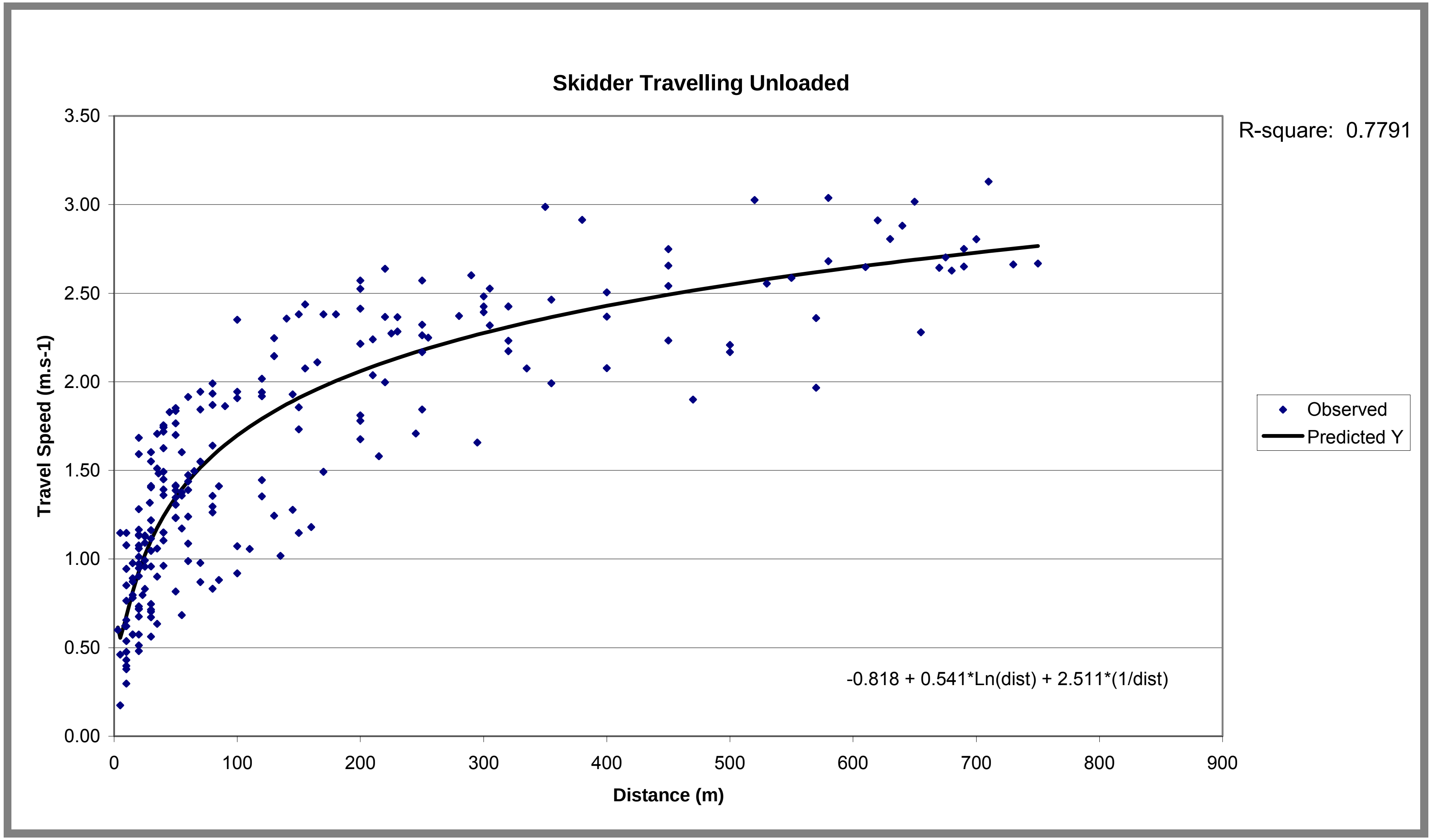
Work Element	Observations Conducted	Observations Required
FB: dist per cycle	119	42
FB: head accumulation 1	119	50
FB: head accumulation 2	119	47
FB: head accumulation 3	119	46
FB: head accumulation 4	119	59
FB: open landing (Step 1)	64	52
FB: open landing (Step 2)	64	55
FB open landing (Step 3)	64	43
SKID: Grapple load	305	217
SKID: collect slash	261	229
DDB1, Op1 cycle time	807	86
DDB1, Op2 cycle time	953	123
DDB2, Op3 cycle time	1,083	88
DDB2, Op4 cycle time	744	175
DDB3, Op5 cycle time	508	188
DDB3, Op6 cycle time	547	113
SLASH: no index X-cut	308	249
SLASH: index X-cut	412	249
SLASH: load from X-cut	427	176
SLASH: load from stack	317	170
SLASH: stack from X-cut	317	142
TRUCK: arrival rate	1,283	865
Stems per bunch	406	80

APPENDIX 3: Skidder Travel Speed Graphs

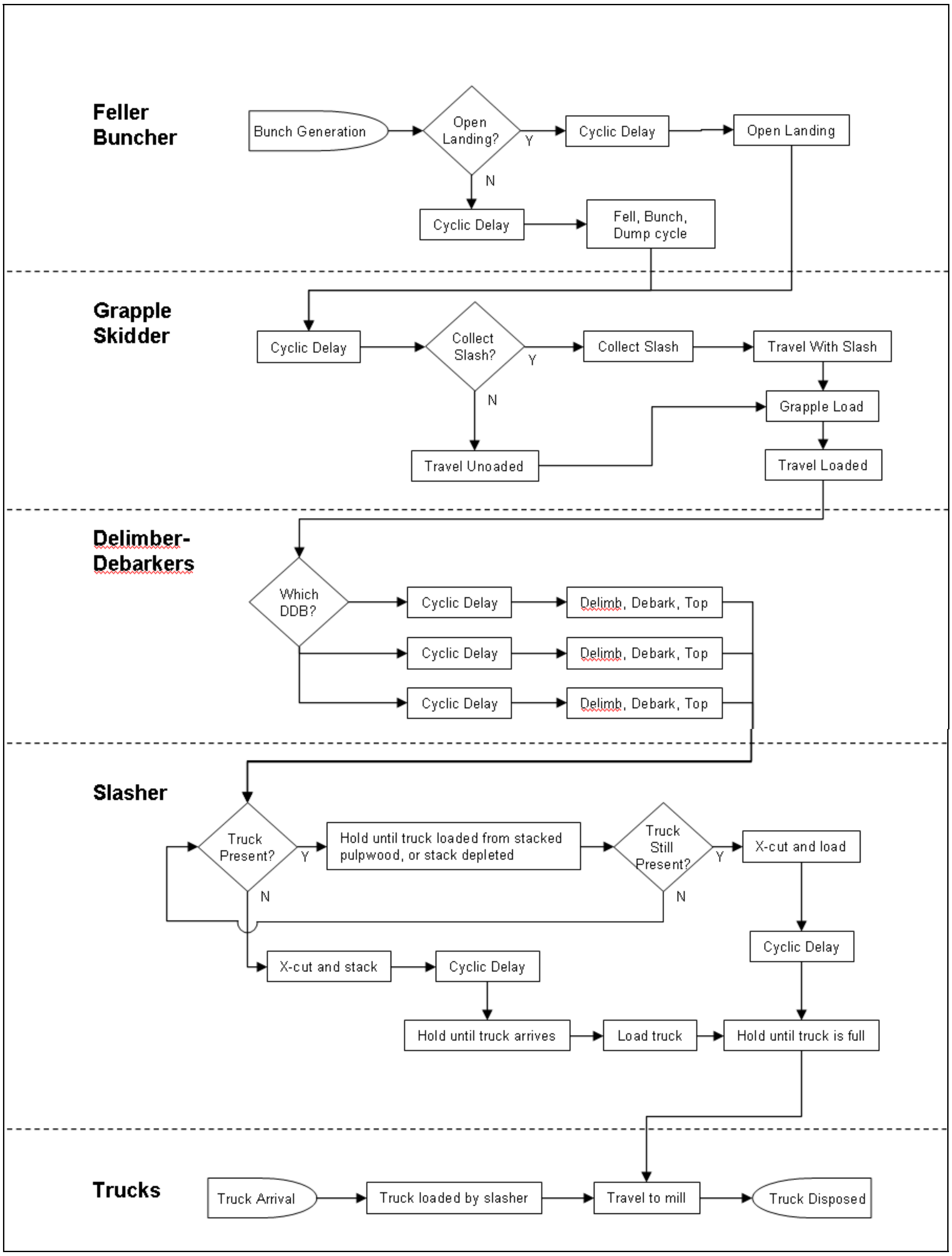




Skidder Travelling with Slash
R-square: 0.6358
Travel Speed (m.s-1)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
500
600
700
800
900
Distance (m)
Observed
Predicted Y
0.003 + 0.404*Ln(dist) - 18.905*(1/dist)

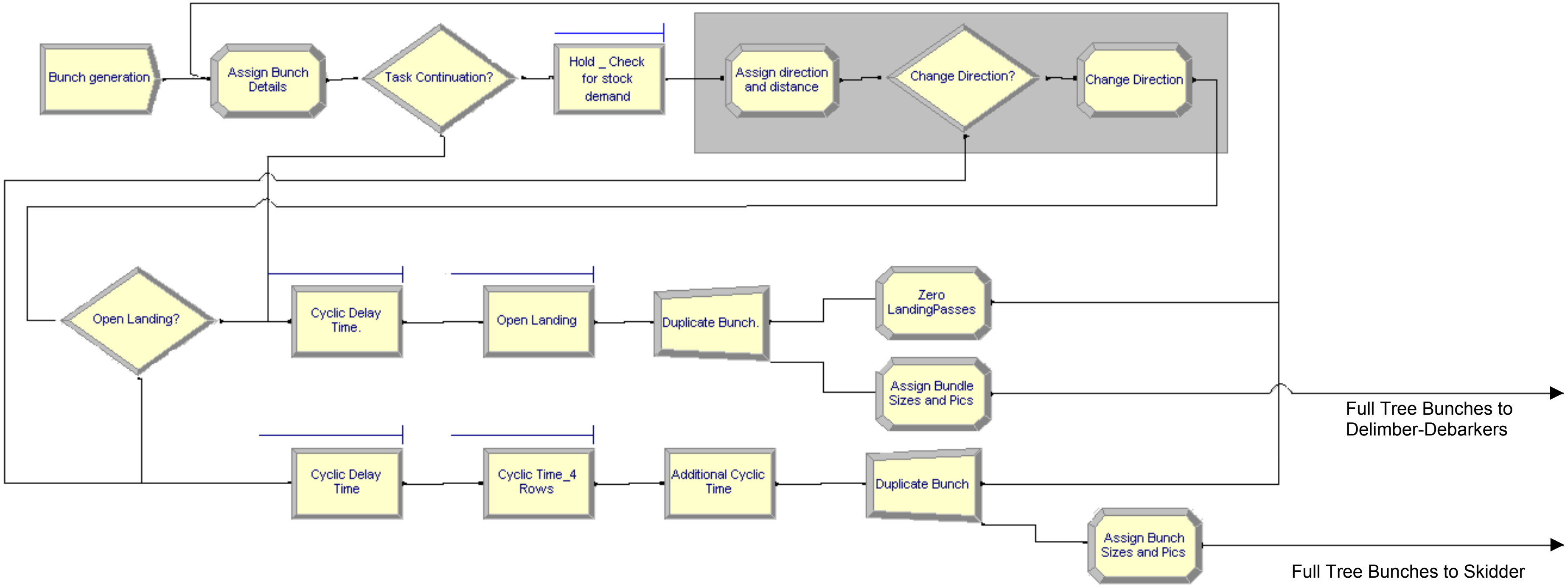

Skidder Travelling Unloaded
R-square: 0.7791
Travel Speed (m.s-1)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
500
600
700
800
900
Distance (m)
Observed
Predicted Y
-0.818 + 0.541*Ln(dist) + 2.511*(1/dist)

APPENDIX 4: Rough Draft Model Flowchart

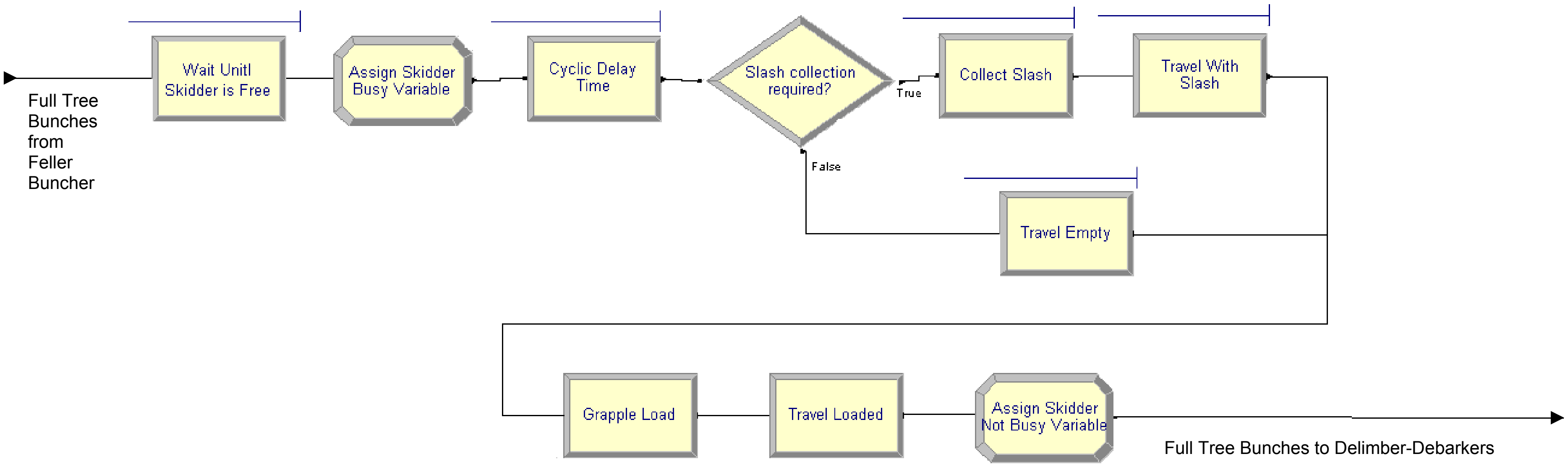


APPENDIX 5: System 1 Simulation Model Flowchart Components

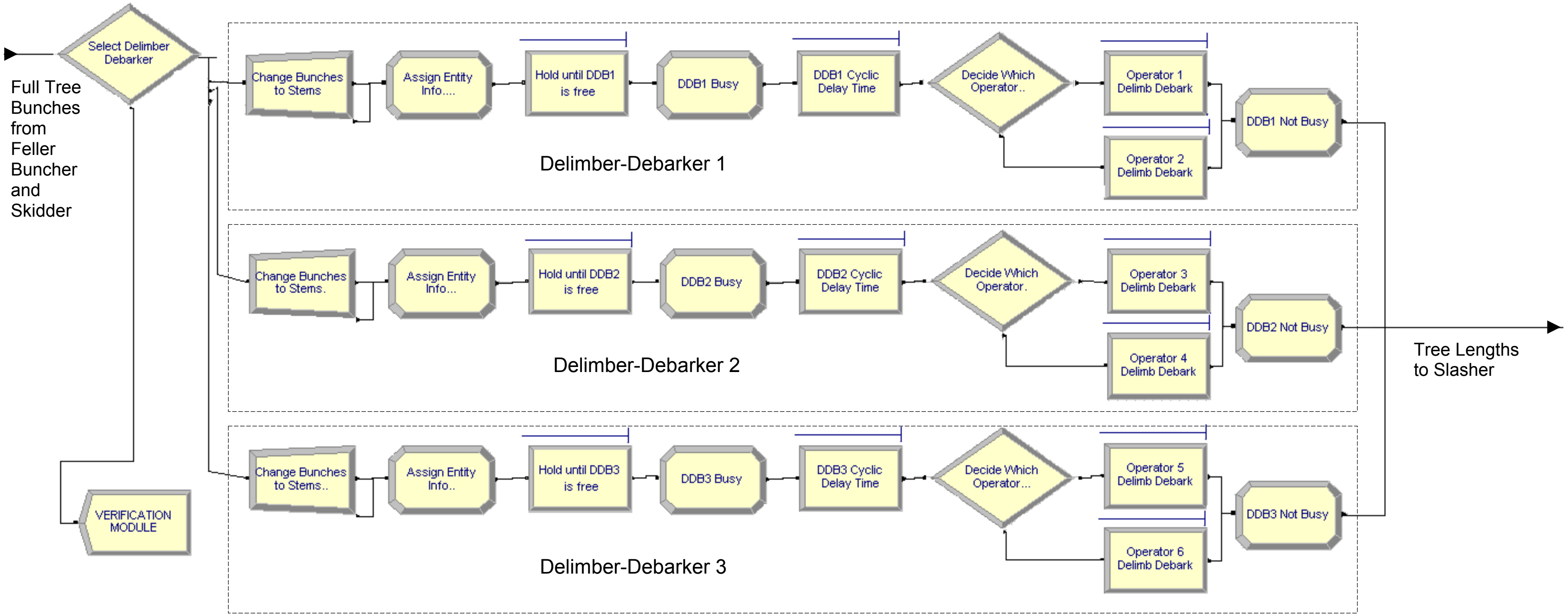
Feller Buncher:



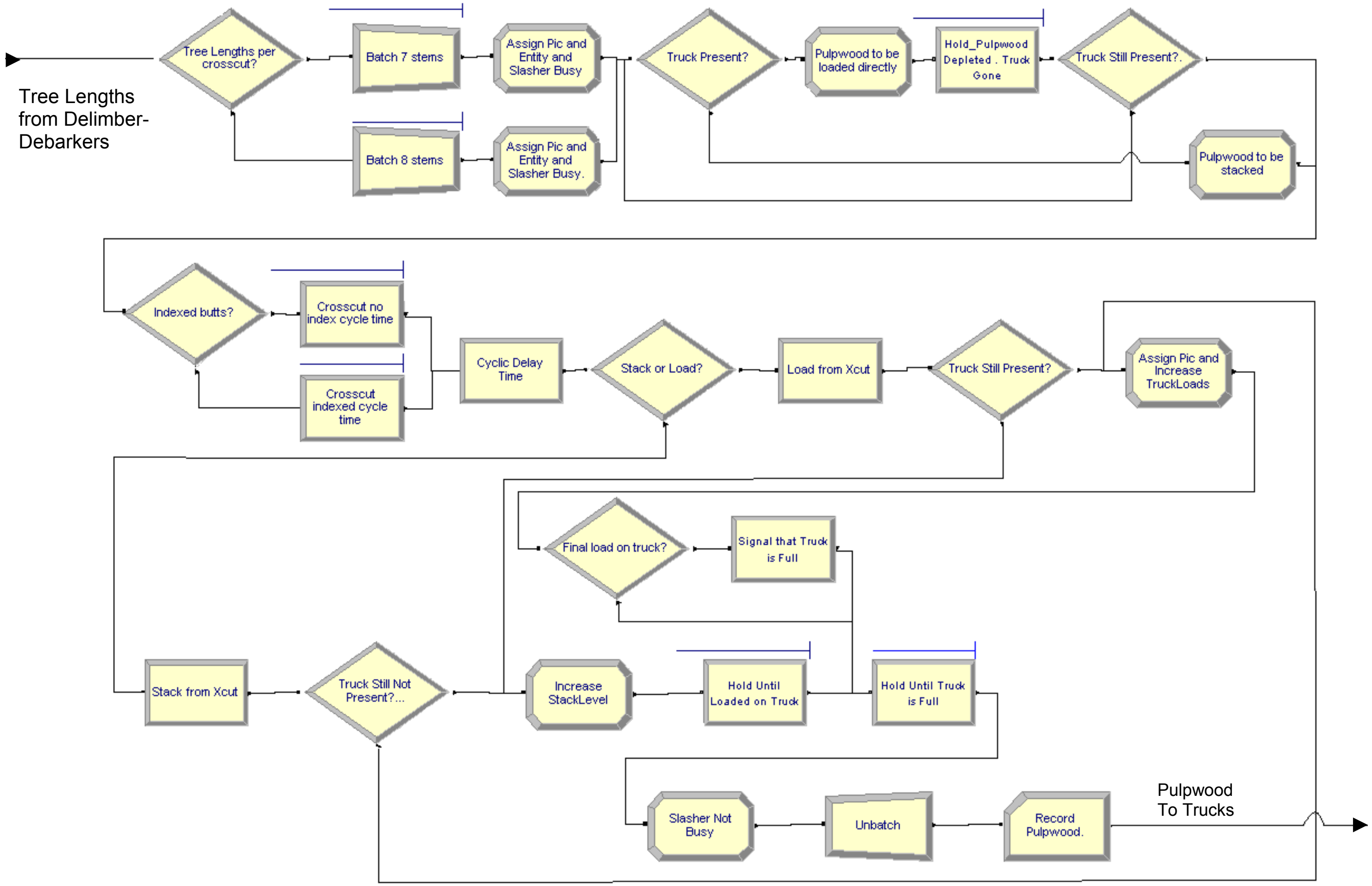
Skidder:


Full Tree Bunches from Feller Buncher
Wait Unitl Skidder is Free
Assign Skidder Busy Variable
Cyclic Delay Time
Slash collection required?
True
False
Collect Slash
Travel With Slash
Travel Empty
Grapple Load
Travel Loaded
Assign Skidder Not Busy Variable
Full Tree Bunches to Delimber-Debarkers

Delimber-Debarkers:

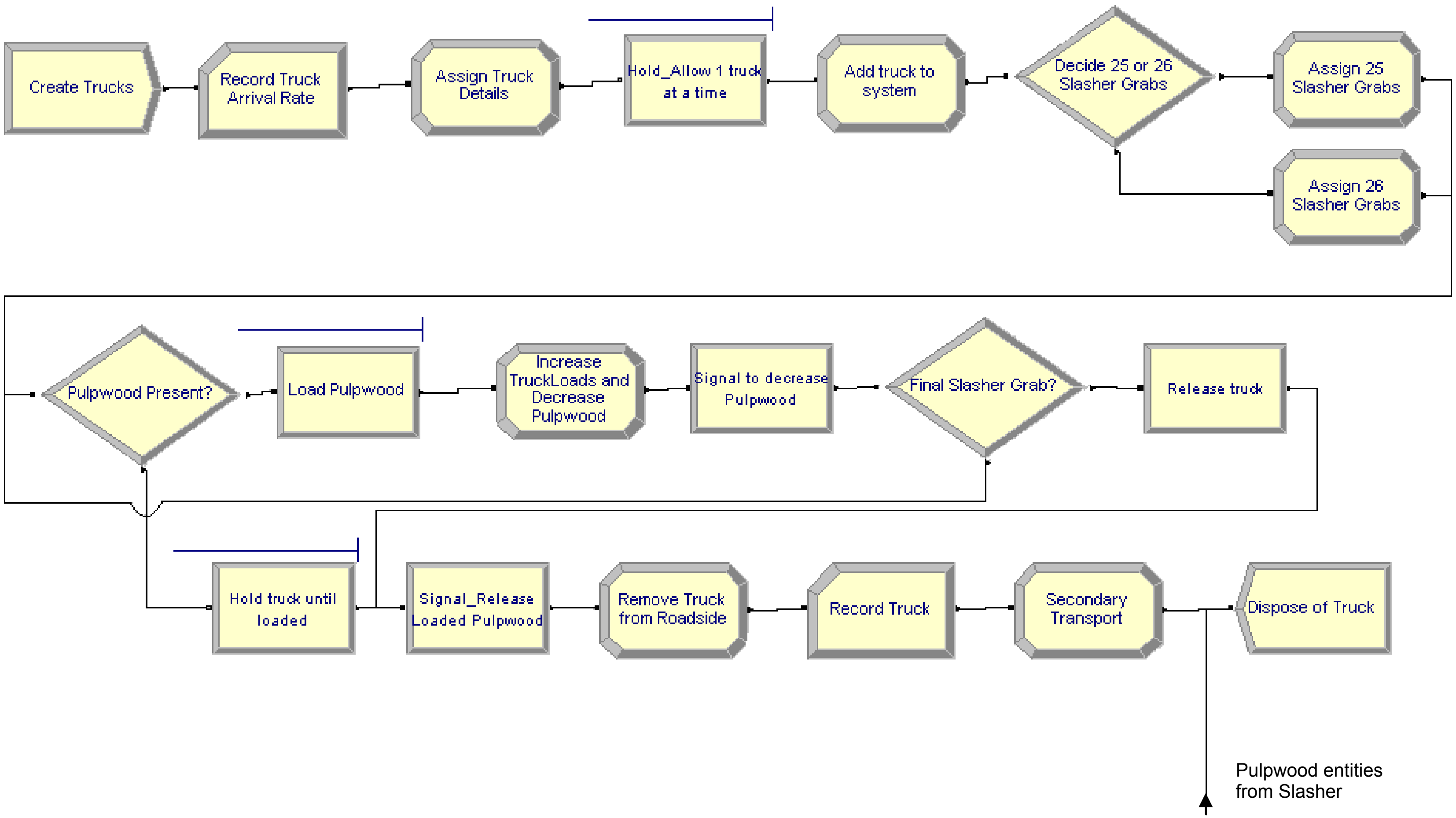


Slasher:

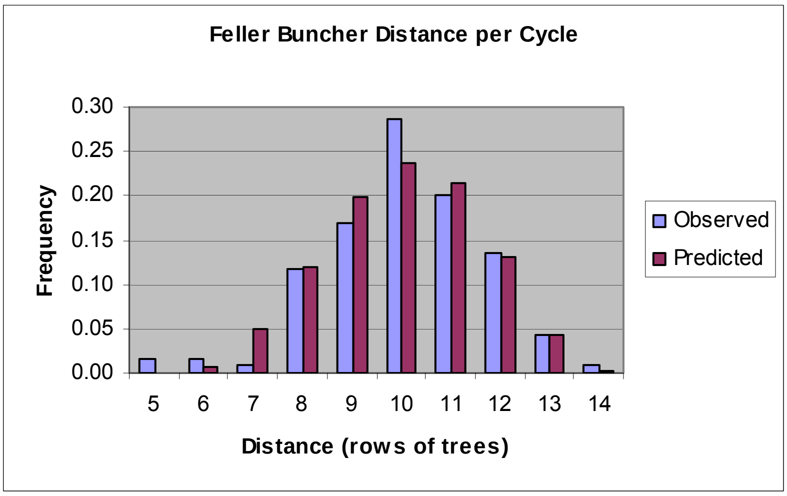


Tree Lengths from Delimber-Debarkers
Tree Lengths per crosscut?
Batch 7 stems
Batch 8 stems
Assign Pic and Entity and Slasher Busy
Assign Pic and Entity and Slasher Busy.
Truck Present?
Pulpwood to be loaded directly
Hold_Pulpwood Depleted . Truck Gone
Truck Still Present?.
Pulpwood to be stacked
Indexed butts?
Crosscut no index cycle time
Crosscut indexed cycle time
Cyclic Delay Time
Stack or Load?
Load from Xcut
Truck Still Present?
Assign Pic and Increase TruckLoads
Final load on truck?
Signal that Truck is Full
Stack from Xcut
Truck Still Not Present?...
Increase StackLevel
Hold Until Loaded on Truck
Hold Until Truck is Full
Slasher Not Busy
Unbatch
Record Pulpwood.
Pulpwood To Trucks

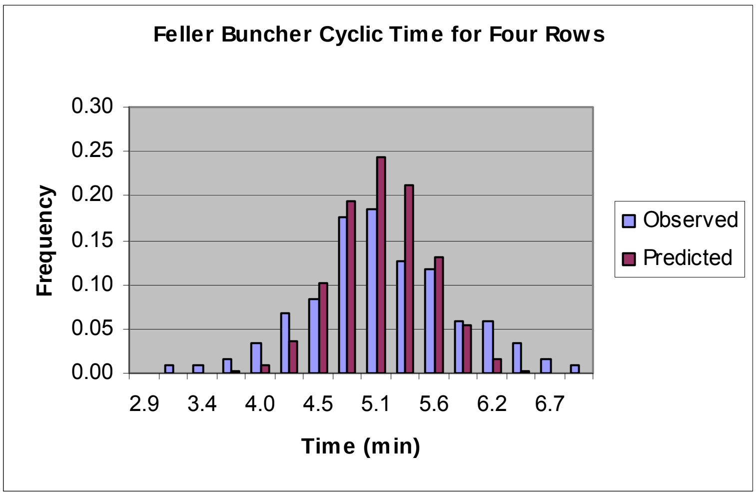
Trucks:


Create Trucks
Record Truck Arrival Rate
Assign Truck Details
Hold_Allow 1 truck at a time
Add truck to system
Decide 25 or 26 Slasher Grabs
Assign 25 Slasher Grabs
Assign 26 Slasher Grabs
Pulpwood Present?
Load Pulpwood
Increase TruckLoads and Decrease Pulpwood
Signal to decrease Pulpwood
Final Slasher Grab?
Release truck
Hold truck until loaded
Signal_Release Loaded Pulpwood
Remove Truck from Roadside
Record Truck
Secondary Transport
Dispose of Truck
Pulpwood entities from Slasher

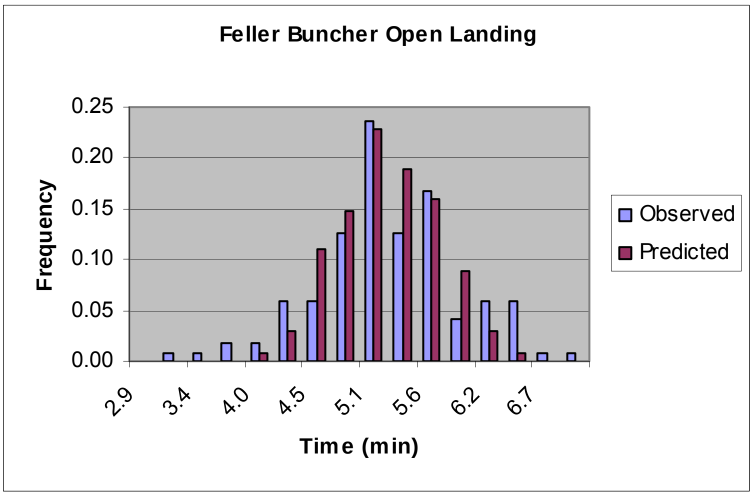
APPENDIX 6: Frequency Distribution Graphs (Modelled versus Real World Outputs)



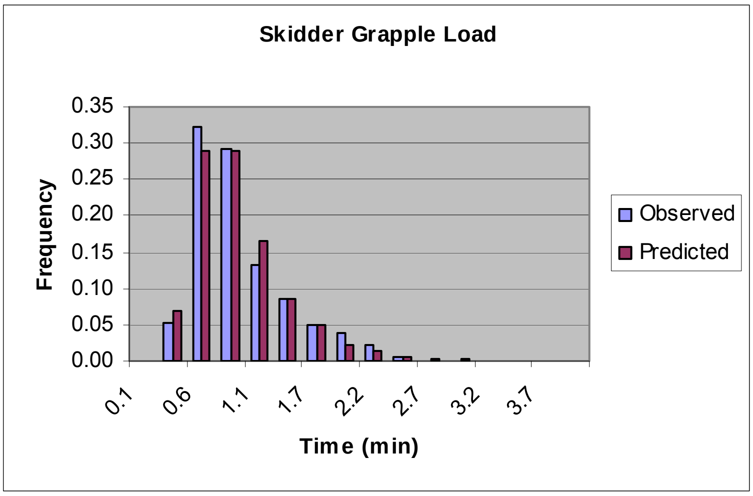
(Beta distribution)



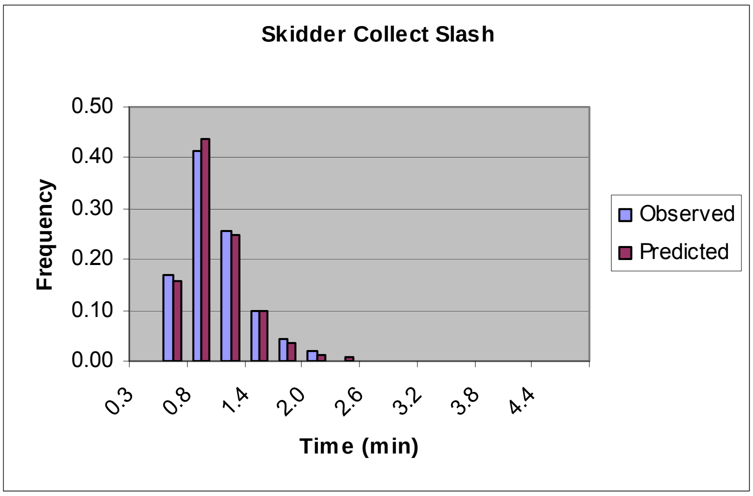
(Weibull distribution)



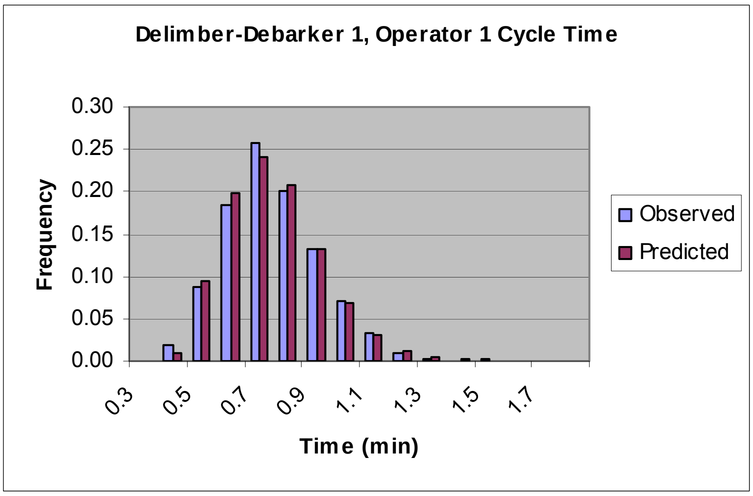
(Weibull distribution)



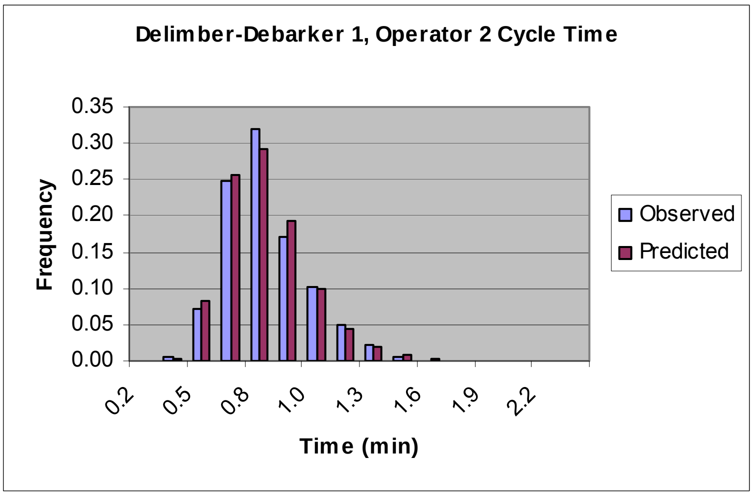
(Lognormal distribution)



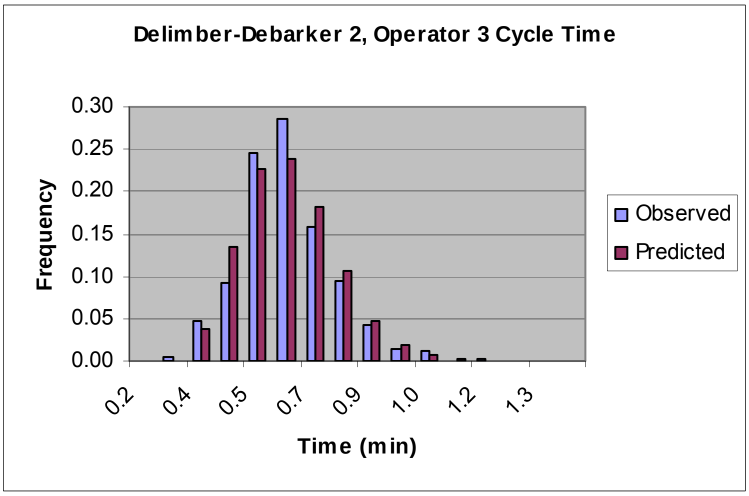
(Lognormal distribution)



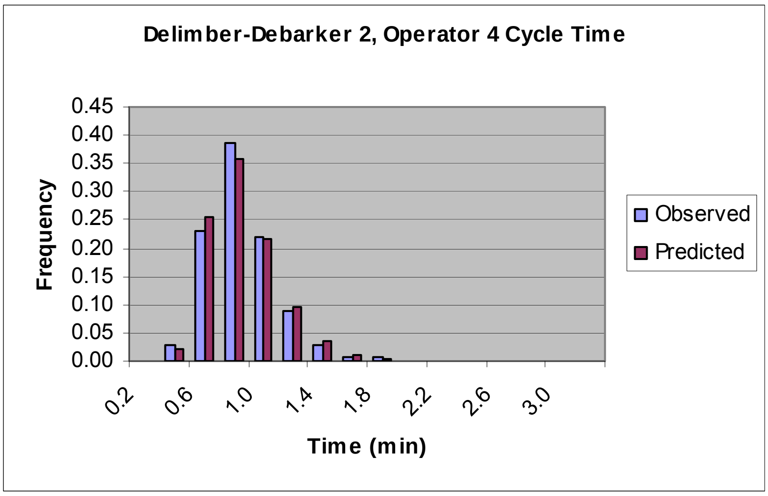
(Erlang distribution)



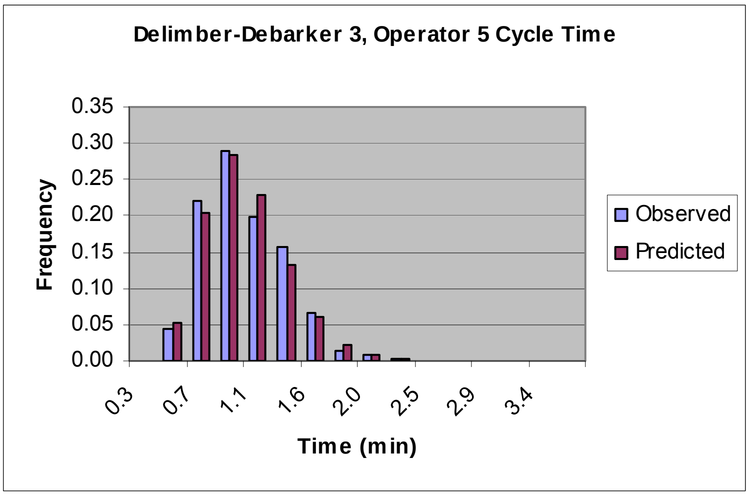
(Lognormal distribution)



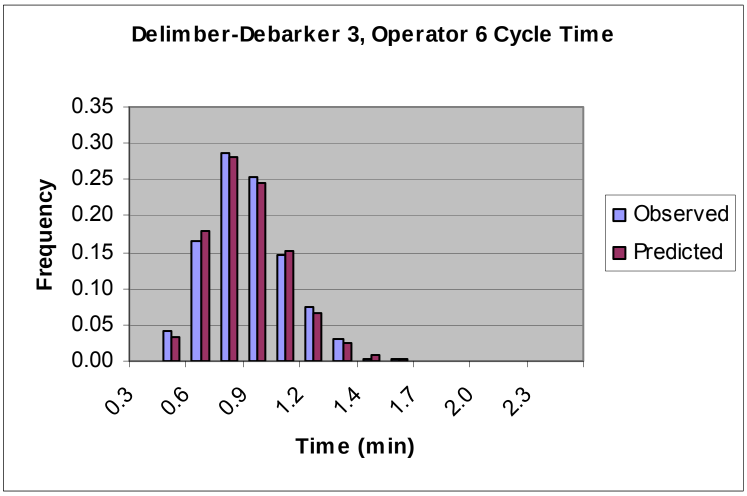
(Erlang distribution)



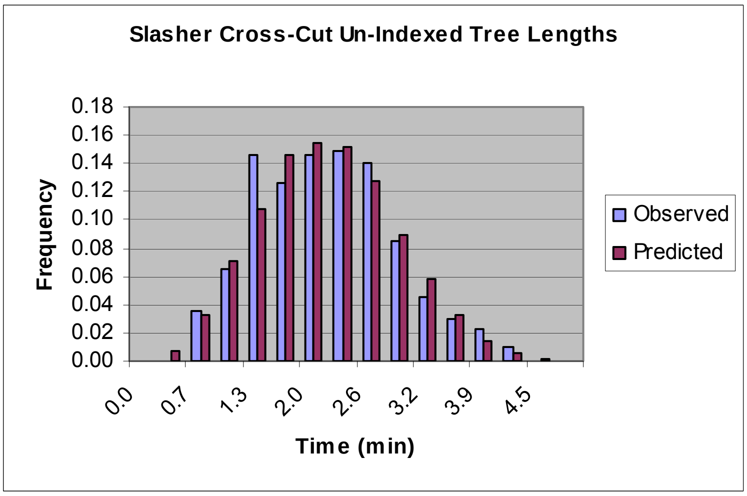
(Lognormal distribution)



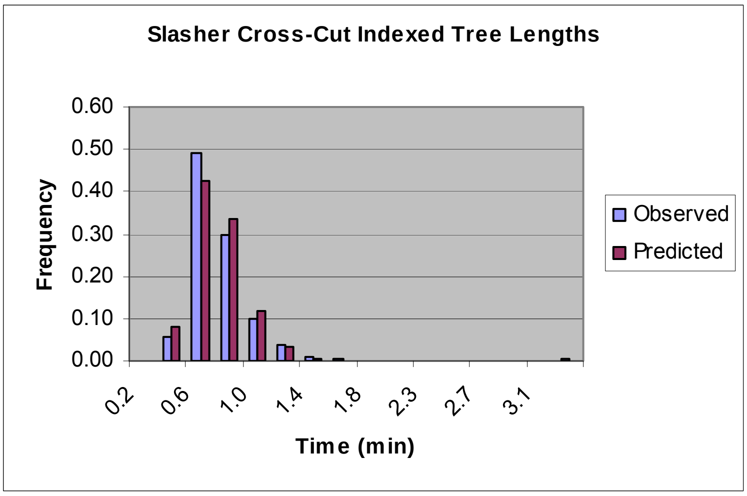
(Erlang distribution)



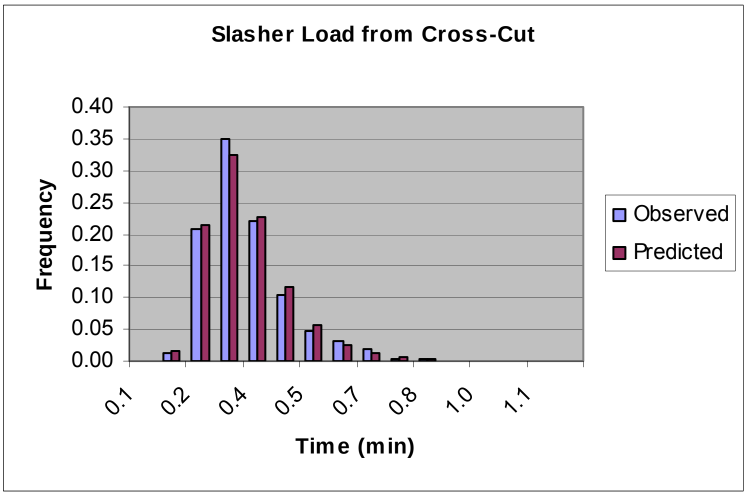
(Erlang distribution)



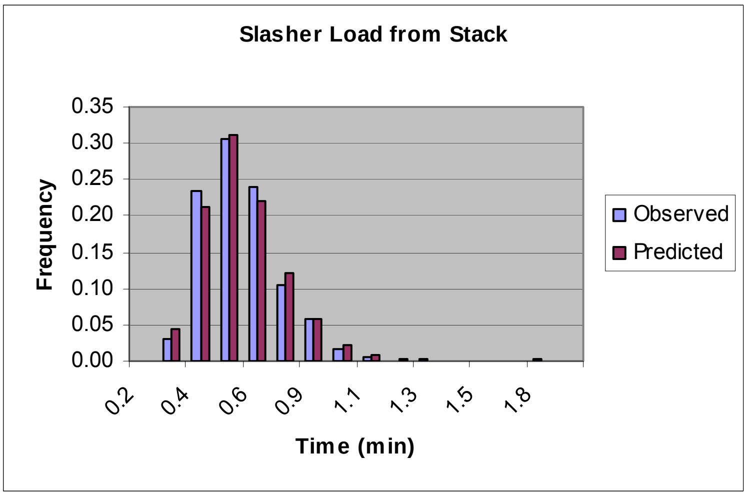
(Weibull distribution)



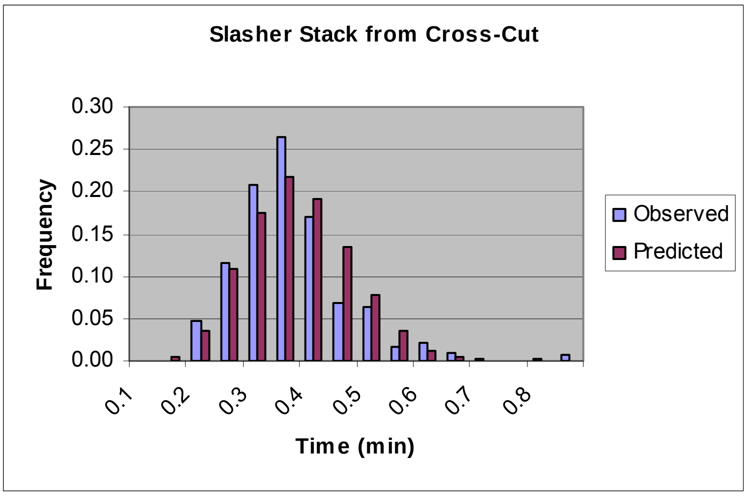
(Lognormal distribution)



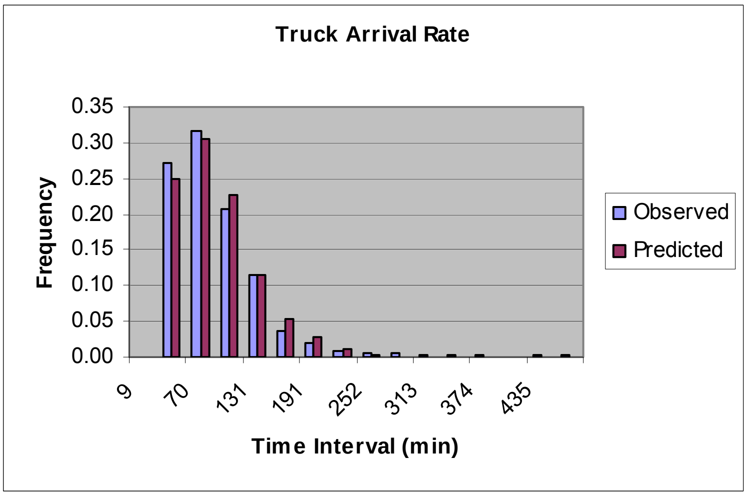
(Lognormal distribution)



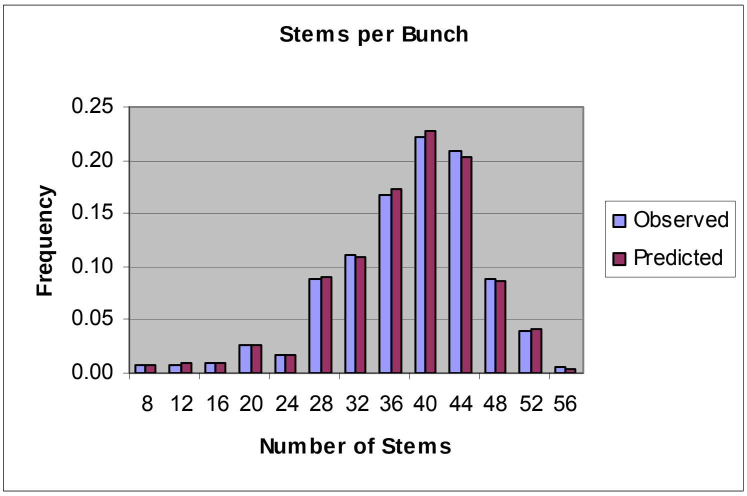
(Lognormal distribution)



(Beta distribution)



(Weibull distribution)



(Empirical distribution)

APPENDIX 7: Cost Categories and Formulas (Hogg *et al*. 2008)

FIXED COSTS	FORMULA
Interest	AAI × i **Where:** AAI = ((P × ((EEL ÷ PMH/year) +1)) + (SV × ((EEL ÷ PMH/year) - 1))) ÷ (2 × (EEL ÷ PMH/year))
Depreciation	(P - Non-depr - SV) ÷ (EEL ÷ PMH/year)
License and Insurance	Lic. and Ins. % of P × P
VARIABE COSTS	**FORMULA**
Fuel	Fuel price/litre × Fuel consumption/PMH
Oil and lubricants	Fuel cons/PMH × Oil and lubricant % of fuel cons. × Oil and lubricant price/litre
Repairs and Maintenance	(P × R) ÷ EEL
Tyres (or Tracks**)**	(((EEL ÷ Tyre life in PMH) × Cost of 1 set of tyres) - Cost of 1 set of tyres) ÷ EEL
PERSONNEL COSTS	**FORMULA**
Direct Personnel Cost	(Driver pay/shift (incl. overtime) × No. of drivers/shift) ÷ PMH/shift
Fringe Benefits	(Direct personnel cost × Fringe benefit %) ÷ PMH/shift

Where:

AAI = Average Annual Investment – Investment amount on which interest will be paid per annum (Rand).

EEL = Expected Economic Life of the machine – Anticipated working life span of the machine (PMH).

i = Interest rate – The rate for money (either borrowed or your own), which should be charged against the capital invested in the machine (%).

Non-depr = Non-depreciable items – The total value of all machine attachments at the time of purchase which do not depreciate with the machine.

P = Purchase Price – The delivered amount paid for the machine, including all attachments, accessories, modifications, delivery charges and taxes (Rand).

R = Repair and maintenance factor (% of P for EEL).

SV = Salvage Value – Estimated market value that the machine will be sold for at the end of its expected economic life (Rand).

APPENDIX 8: Cost Calculation per Machine for System 1 with Three Trucks

MACHINE DESCRIPTION	TIGERCAT 720 D FELLER BUNCHER WITH DISC SAW
OPERATION	FELLING AND BUNCHING EUCALYPTUS PULPWOOD TREES

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

FIXED COSTS

Machine Purchase Price	1,618,400	R
Cost of Tyres	129,996	R
Residual Value (% of Purchase Price)	10%	
Workplace Time	11.00	hrs
Machine Utilisation	55.9	%
Non-Productive Machine Hours / Shift	4.85	hrs
Productive Machine Hours / Shift	6.15	hrs
Shifts / Day	1	
Average Productive Hours / Day	6.15	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	1917	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	9586	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	101,959	R/annum
License and Insurance	80,920	R/annum
Depreciation	265,313	R/annum
Total Fixed Cost	**448,192**	**R/annum**
Fixed Cost / Productive hr	**233.76**	**R / hr**

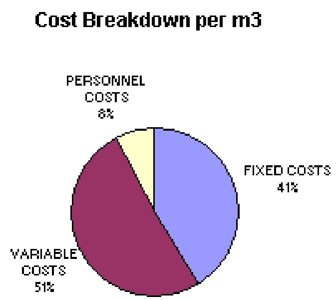
VARIABLE COSTS

R & M (% Purchase Price)	70	%
Fuel Consumption	27.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	3.0	%
Oil Price	17.00	R / L
Life of Tryres	5000	hrs
Cost of Tyres	129,996	R
R & M Cost / Productive hr	118.18	R / hr
Fuel Cost / Productive hr	148.72	R / hr
Oil Cost / Productive hr	13.77	R / hr
Tyre Cost / Productive hr	12.44	R / hr
Variable Cost per Productive hr	**293.10**	**R / hr**

PERSONNEL COSTS

Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	30	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	33.20	R / hr
Benefits Personnel Cost / Productive hr	9.96	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**43.16**	**R / hr**

SUMMARY



Fixed Cost per Productive hr	233.76	R / hr
Variable Cost per Productive hr	293.10	R / hr
Personnel Cost / Productive hr	43.16	R / hr
Total Cost / Productive hr	**570.02**	**R / hr**
Production per Productive hr	**93.0**	**m3**
Total Cost / m3	**6.13**	**R / m3**

MACHINE DESCRIPTION	TIGERCAT 630C SKIDDER
OPERATION	SKIDDING EUCALYPTUS FULL TREE PULPWOOD BUNCHES TO ROADSIDE

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

FIXED COSTS

Machine Purchase Price	1952824	R
Cost of Tyres	129996	R
Residual Value (% of Purchase Price)	10%	
Workplace Time	11.00	hrs
Machine Utilisation	83.0	%
Non-Productive Machine Hours / Shift	1.88	hrs
Productive Machine Hours / Shift	9.12	hrs
Shifts / Day	1	
Average Productive Hours / Day	9.12	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	2847	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	14235	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	123028	R/annum
License and Insurance	97641	R/annum
Depreciation	364175	R/annum
Total Fixed Cost	584844	**R/annum**
Fixed Cost / Productive hr	**205.43**	**R / hr**

VARIABLE COSTS

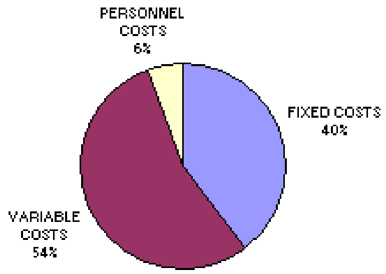
R & M (% Purchase Price)	70	%
Fuel Consumption	27.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	3.0	%
Oil Price	17.00	R / L
Life of Tryres	4000	hrs
Cost of Tyres	129996	R
R & M Cost / Productive hr	96.03	R / hr
Fuel Cost / Productive hr	148.72	R / hr
Oil Cost / Productive hr	13.77	R / hr
Tyre Cost / Productive hr	23.37	R / hr
Variable Cost per Productive hr	**281.88**	**R / hr**

PERSONNEL COSTS

Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	30	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	22.36	R / hr
Benefits Personnel Cost / Productive hr	6.71	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**29.06**	**R / hr**

SUMMARY

Cost Breakdown per m3



Fixed Cost per Productive hr	205.43	R / hr
Variable Cost per Productive hr	281.88	R / hr
Personnel Cost / Productive hr	29.06	R / hr
Total Cost / Productive hr	**516.37**	**R / hr**
Production per Productive hr	**57.3**	**m3**
Total Cost / m3	**9.02**	**R / m3**

MACHINE DESCRIPTION	DDB1 - EXCAVATOR-BASED DELIMBER-DEBARKER WITH SP 650 HEAD
OPERATION	DELIMBING AND DEBARKING EUCALYPTUS PULPWOOD

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

FIXED COSTS

Machine Purchase Price	1602216	R
Cost of Tracks	81600	R
Residual Value (% of Purchase Price)	12%	
Workplace Time	11.0	hrs
Machine Utilisation	85.3	%
Non-Productive Machine Hours / Shift	1.62	hrs
Productive Machine Hours / Shift	9.38	hrs
Shifts / Day	1	
Average Productive Hours / Day	9.38	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	2926	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	14631	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	100940	R/annum
License and Insurance	80111	R/annum
Depreciation	303739	R/annum
Total Fixed Cost	484789	**R/annum**
Fixed Cost / Productive hr	**165.67**	**R / hr**

VARIABLE COSTS

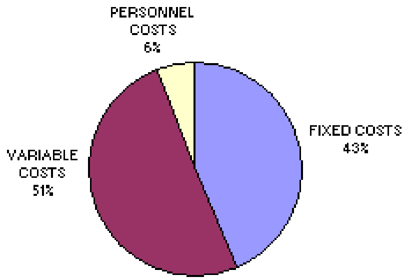
R & M (% Purchase Price)	70	%
Fuel Consumption	17.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	8.0	%
Oil Price	17.00	R / L
Life of Tracks	10000	hrs
Cost of Tracks	81600	R
R & M Cost / Productive hr	76.66	R / hr
Fuel Cost / Productive hr	93.64	R / hr
Oil Cost / Productive hr	23.12	R / hr
Track Cost / Productive hr	2.58	R / hr
Variable Cost per Productive hr	**195.99**	**R / hr**

PERSONNEL COSTS

Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	0	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	21.75	R / hr
Benefits Personnel Cost / Productive hr	0.00	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**21.75**	**R / hr**

SUMMARY

Cost Breakdown per m3



Fixed Cost per Productive hr	165.67	R / hr
Variable Cost per Productive hr	195.99	R / hr
Personnel Cost / Productive hr	21.75	R / hr
Total Cost / Productive hr	**383.42**	**R / hr**
Production per Productive hr	**23.6**	**m3**
Total Cost / m3	**16.24**	**R / m3**

MACHINE DESCRIPTION	DDB2 - EXCAVATOR-BASED DELIMBER-DEBARKER WITH SP 551 HEAD
OPERATION	DELIMBING AND DEBARKING EUCALYPTUS PULPWOOD

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

FIXED COSTS

Machine Purchase Price	1602216	R
Cost of Tracks	81600	R
Residual Value (% of Purchase Price)	12%	
Workplace Time	11.0	hrs
Machine Utilisation	83.5	%
Non-Productive Machine Hours / Shift	1.82	hrs
Productive Machine Hours / Shift	9.18	hrs
Shifts / Day	1	
Average Productive Hours / Day	9.18	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	2865	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	14326	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	100940	R/annum
License and Insurance	80111	R/annum
Depreciation	303739	R/annum
Total Fixed Cost	484789	**R/annum**
Fixed Cost / Productive hr	**169.20**	**R / hr**

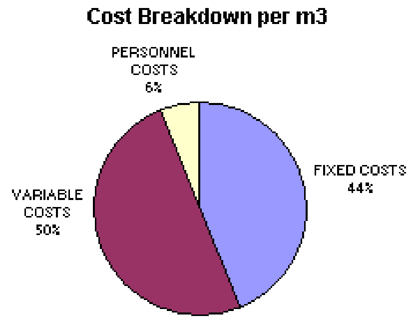
VARIABLE COSTS

R & M (% Purchase Price)	70	%
Fuel Consumption	17.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	8.0	%
Oil Price	17.00	R / L
Life of Tracks	10000	hrs
Cost of Tracks	81600	R
R & M Cost / Productive hr	78.29	R / hr
Fuel Cost / Productive hr	93.64	R / hr
Oil Cost / Productive hr	23.12	R / hr
Track Cost / Productive hr	2.46	R / hr
Variable Cost per Productive hr	**197.51**	**R / hr**

PERSONNEL COSTS

Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	0	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	22.21	R / hr
Benefits Personnel Cost / Productive hr	0.00	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**22.21**	**R / hr**

SUMMARY



Fixed Cost per Productive hr	169.20	R / hr
Variable Cost per Productive hr	197.51	R / hr
Personnel Cost / Productive hr	22.21	R / hr
Total Cost / Productive hr	**388.92**	**R / hr**
Production per Productive hr	**21.5**	**m3**
Total Cost / m3	**18.12**	**R / m3**

MACHINE DESCRIPTION	DDB3 - EXCAVATOR-BASED DELIMBER-DEBARKER WITH SP 650 HEAD
OPERATION	DELIMBING AND DEBARKING EUCALYPTUS PULPWOOD

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

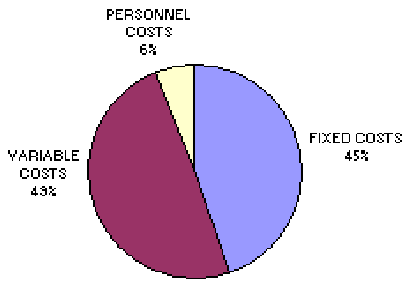
FIXED COSTS		
Machine Purchase Price	1602216	R
Cost of Tracks	81600	R
Residual Value (% of Purchase Price)	12%	
Workplace Time	11.0	hrs
Machine Utilisation	76.0	%
Non-Productive Machine Hours / Shift	2.65	hrs
Productive Machine Hours / Shift	8.35	hrs
Shifts / Day	1	
Average Productive Hours / Day	8.35	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	2607	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	13034	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	100940	R/annum
License and Insurance	80111	R/annum
Depreciation	303739	R/annum
Total Fixed Cost	484789	**R/annum**
Fixed Cost / Productive hr	**185.98**	**R / hr**

VARIABLE COSTS		
R & M (% Purchase Price)	70	%
Fuel Consumption	17.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	8.0	%
Oil Price	17.00	R / L
Life of Tracks	10000	hrs
Cost of Tracks	81600	R
R & M Cost / Productive hr	86.05	R / hr
Fuel Cost / Productive hr	93.64	R / hr
Oil Cost / Productive hr	23.12	R / hr
Track Cost / Productive hr	1.90	R / hr
Variable Cost per Productive hr	**204.71**	**R / hr**

PERSONNEL COSTS		
Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	0	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	24.42	R / hr
Benefits Personnel Cost / Productive hr	0.00	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**24.42**	**R / hr**

SUMMARY

Cost Breakdown per m3



Fixed Cost per Productive hr	185.98	R / hr
Variable Cost per Productive hr	204.71	R / hr
Personnel Cost / Productive hr	24.42	R / hr
Total Cost / Productive hr	**415.10**	**R / hr**
Production per Productive hr	**17.1**	**m3**
Total Cost / m3	**24.22**	**R / m3**

MACHINE DESCRIPTION	EXCAVATOR-BASED SLASHER
OPERATION	SLASHING 5.5m PULPWOOD LENGTHS AND LOADING ONTO TRUCKS

NOTE: SIMULATION RUN RESULTS AND STANDARD COST INPUTS HAVE BEEN USED TO PRODUCE THIS COSTING EXERCISE. COSTS RELEVANT TO STUDY CONDITIONS IN 2007.

COST ANALYSIS:

FIXED COSTS

Machine Purchase Price	1375776	R
Cost of Tracks	81600	R
Residual Value (% of Purchase Price)	12%	
Workplace Time	11.0	hrs
Machine Utilisation	76.0	%
Non-Productive Machine Hours / Shift	2.64	hrs
Productive Machine Hours / Shift	8.36	hrs
Shifts / Day	1	
Average Productive Hours / Day	8.36	hrs
Working Days / Year	312	days
Idle Days / Year	0	days
Annual Productive Machine Hours	2607	hrs
Expected Economic Life (yrs)	5.0	yrs
Expected Economic Life (PMH)	13035	hours
Interest Rate	10.50	%
License and Insurance (% Purchase Price)	5.0	%
Cost of Capital	86674	R/annum
License and Insurance	68789	R/annum
Depreciation	258505	R/annum
Total Fixed Cost	413968	**R/annum**
Fixed Cost / Productive hr	**158.79**	**R / hr**

VARIABLE COSTS

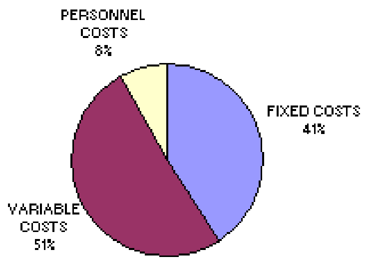
R & M (% Purchase Price)	70	%
Fuel Consumption	17.0	L / hr
Fuel Price	5.51	R / L
Oil Consumption (% Fuel Consumption)	10.0	%
Oil Price	17.00	R / L
Life of Tracks	10000	hrs
Cost of Tracks	81600	R
R & M Cost / Productive hr	73.88	R / hr
Fuel Cost / Productive hr	93.64	R / hr
Oil Cost / Productive hr	28.90	R / hr
Track Cost / Productive hr	1.90	R / hr
Variable Cost per Productive hr	**198.32**	**R / hr**

PERSONNEL COSTS

Driver Pay / Shift (incl. overtime)	204.00	R
No of Drivers / Shift	1	
Worker Pay / Shift (incl. overtime)	0.00	R
No. Workers/Shift	0	
Fringe Benefits (% of wage)	30	%
Supervision (% wage)	0	%
Direct Personnel Cost / Productive hr	24.41	R / hr
Benefits Personnel Cost / Productive hr	7.32	R / hr
Supervision Cost / Productive hr	0.00	R / hr
Personnel Cost / Productive hr	**31.74**	**R / hr**

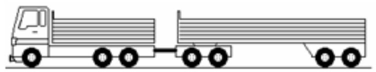
SUMMARY

Cost Breakdown per m3



Fixed Cost per Productive hr	158.79	R / hr
Variable Cost per Productive hr	198.32	R / hr
Personnel Cost / Productive hr	31.74	R / hr
Total Cost / Productive hr	**388.84**	**R / hr**
Production per Productive hr	**60.1**	**m3**
Total Cost / m3	**6.47**	**R / m3**

RIGID FIXED COST INPUTS					
Cost Price (excl VAT)				R	1,151,870
Residual Value				%	20.0%
Finance - Cost of Capital (Interest)				%	10.5%
- or Monthly Repayment				R	0
Depreciation - Distance km	0	or	Time	yrs	5.0
Insurance (% of Cost Price)				%	7.0%
Tare	9,080	kg	Licence	R	9,048
Number of Steering Axle(s)				no	1
Number of Tyres (excl spare)				no	10
Tyre Size				-	315/80R22.5
Tyre Price - New Tyre (excl VAT)				R	5,943
- Retread (excl VAT)				R	879
New Tyre Life - Front & Rear			80,000	km	100,000
Retread Tyre Life - Front & Rear			80,000	km	100,000
Number of Retreads - Front & Rear			0.0	no	2.0
TRAILER FIXED COST INPUTS					
Cost Price (excl VAT) (1st + 2nd Trailer)				R	275,408
Residual Value				%	10.0%
Finance - Cost of Capital (Interest)				%	10.5%
- or Monthly Repayment				R	0
Depreciation - Time				yrs	5.0
Insurance (% of Cost Price)				%	5.0%
Tare - First Trailer	8,100	kg	Licence	R	6,720
Tare - Second Trailer	0	kg	Licence	R	0
Number of Axle(s)				no	4
Number of Tyres (excl spares)				no	16
Tyre Size				-	315/80R22.5
Tyre Price - New Tyre (excl VAT)				R	5,943
- Retread (excl VAT)				R	908
New tyre life				km	120,000
Retread tyre life				km	120,000
Number of Retreads				no	2.0
VARIABLE COST INPUTS					
Fuel Consumption				Litre / 100 km	57.0
Fuel Price				Cent / Litre	550.8
Lubricants (as % of fuel cost)				%	2.5%
Maintenance				cpk	126.8
Other Variable Running Costs				cpk	0.0
PERSONNEL COST INPUTS					
Drivers - Monthly Cost				R	17,151
Assistants -Monthly Cost				R	0
UTILISATION					
Annual Kilometres				km	98,648
Days Worked per Annum				days	312
Timber served per annum				m3	49844



FIXED COSTS	R/annum	cpk	%	%
Cost of Capital (Finance)	100,751	102.1	24.3%	8.9%
Depreciation	202,969	205.8	49.0%	17.9%
Insurance	94,401	95.7	22.8%	8.3%
Licence	15,768	16.0	3.8%	1.4%
Other	0	0.0	0.0%	0.0%
TOTAL FIXED COSTS	413,889	420	100.0%	36.6%
VARIABLE COSTS	R/annum	cpk	%	%
Fuel	309,711	314.0	60.5%	27.4%
Lubricants	7,743	7.8	1.5%	0.7%
Maintenance	125,113	126.8	24.5%	11.1%
Tyres	68,935	69.9	13.5%	6.1%
Other	0	0.0	0.0%	0.0%
TOTAL VARIABLE COSTS	511,503	518.5	100.0%	45.2%
PERSONNEL COSTS	R/annum	cpk	%	%
Personnel	205,812	208.6	100.0%	18.2%
TOTAL COSTS	**1,131,204**	**1,146.7**	---	**100.0%**

Cost per m3	22.69