Analysis of a mechanised cut-to-length harvesting operation working in a poor growth *Eucalyptus smithii* stand through use of discrete-event simulation in R

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Abstract

Mechanised timber harvesting operations are rapidly increasing in South Africa, particularly in *Eucalyptus* pulpwood production. There are however still considerable inefficiencies in implementation and evidence of unnecessary operational variability in current mechanised systems.

A typical South African cut-to-length operation for harvesting *Eucalyptus* pulp logs utilising two excavator-based harvesters and one purpose-built forwarder was studied. The ability of performing discrete-event simulation using R was tested. One of the harvesters and the forwarder were simulated individually and alternative work methods were modelled and compared against the original work method. The changes in productivity based on productive machine hours and cost were recorded. The input data was negatively affected by the large variation in stand and individual tree characteristics. This led to a decrease in model validity. Machine simulation models where however able to capture trends found by other authors.

The current method of felling a combination of the four and five tree wide swaths yielded the highest productivity of 11.43 m^3 hr^{-1}. Tree size had a notable effect on both the harvester and forwarder productivity. Increasing the tree size from 0.14 m^3 to 0.20 m^3 and 0.3 m^3 led to productivity increases of 5.26 m^3 hr^{-1} and 13.14 m^3 hr^{-1}, respectively. When comparing the original mean stack sizes of 2.5 m^3, stacks with a mean volume of 5.4 m^3 yielded an increase in productivity of 5.91 m^3 hr^{-1}. Fitting a larger grapple (1 m^2 vs. original 0.8 m^2 opening) to the forwarder showed increased productivities across all stack sizes. Forwarder productivity decreased by up to 17.8% with an increase in extraction distance. The largest decrease in forwarder productivity was noted when increasing the on-road travel (both loaded and unloaded) distance from 0 m to 100 m (single road scenario); decreasing by 6.1% when using the standard grapple and 7.6% when using the larger grapple. When using both roads the largest productivity decreases were found when increasing the on-road extraction distance from 0 m to 200 m; decreasing by 15.3% when using the standard grapple and 17.8% when using the larger grapple. Costing of each individual machine was carried out per alternative scenario. Decreases in harvester cost were noted between increasing tree sizes, and forwarder cost increased with extraction distance. Harvester cost decreased by as much as R35.24 m^{-3} when

increasing mean tree volume from 0.14 m^3 to 0.3 m^3, whereas forwarding cost decreased by a maximum of R1.13 m^{-3} when extracting larger stacks (5.4 m^3), when compared to the observed system (2.5 m^3 stacks). Removal of all road travel elements and piling directly at roadside, showed savings of up to R10.21 m^{-3} when compared to the observed system. R proved to be useful for carrying out discrete-event simulations, however, dedicated simulation probability distributions need to be developed before it can be said that R is highly suitable for discrete-event simulation.

Opsomming

Aangesien die gebruik van meganiseede hout ontginning operasies in Suid-Afrika vinnig toeneem, veral in die produksie van *Eucalyptus* pulp, is die implementering van produktiewe sisteme dringend nodig. Die implementering van hierdie sisteme is nog baie oneffektief en daar is tans baie variasie in die toepassing. ’n Tipiese Suid-Afrikaanse sny-na-lengte ontginnings operasie is ondersoek, dit het twee laaigraaf-baseerde enkelgreepontginners en een ekstraksie voertuig (“forwarder”) wat spesiaal gebou is, ingesluit. Die vermoë om afsonderlike gebeurtenis simulasie met gebruik van R uit te voer, is getoets. Een van die enkelgreepontginners en die ekstraksie voertuig is individueel nageboots. Behalwe vir die huidige sisteem is alternatiewe metodes gemodelleer en met die oorspronklike werksmetode vergelyk. Die veranderinge in produktiwiteit en koste is aangeteken. Die insetgegewe is weens die groot variasie in kenmerke van groepe bome negatief beïnvloed. Dit het gelei tot ’n afname in die geldigheid van die model. Die masjien modelle het egter dieselfde neigings getoon as wat die ander outears beskryf. Die huidige metodes om vier tot vyf tree wye stroke af te kap, het gelei tot die hoogste produktiwiteit van 11. 43 m^3 per uur $^{-1}$. Die grootte van die boom het ’n merkwaardige effek gehad op die produktiwiteit van die enkelgreepontginner asook die produktiwiteit van die ekstraksie voertuig. Die verhoging van die boomgrootte vanaf 0.14 m^3 tot 0.20 m^3 en 0.3 m^3 het gelei tot ’n toename in die produktiwiteit van 5.26 m^3 per uur $^{-1}$ en 13.14 m^3 per uur $^{-1}$ onderskeidelik. Intussen het stapels met ’n volume van 5.4 m^3 gelei tot ’n middelterm van 5.4 m^3 en ’n toename in produktiwiteit van 5.91 m^3 per uur. Die gebruik van ’n groter gryphaak (1 m^2) het met betrekking tot alle stapelgroottes gelei tot hoër produktiwiteit. Die produktiwiteit van die ekstraksie voertuig het as gevolg van die toename in vervoer afstand met tot 17.8% afgeneem. Die grootste afnames is tussen afstandtussenposes 0 m en 100 m (enkelpad scenario’s) asook 0 m en 200 m (dubbelpad scenario’s) opgemerk. Die kosteberekening van elke individuele masjien is per scenario gedoen. Afnames in die koste van die enkelgreepontginner is opgemerk by toenames in boomgrootte, en die koste van die enkelgreepontginner het toegeneem met die vervoer afstand. Ontginnings kostes het met ’n maksimum van R35.24 afgeneem met ’n toename in boomvolume, terwyl die ekstraksie voertuig koste tot ’n maksimum van R1.13 per siklus afgeneem het wanneer groter stapels vervoer is. ’n Afname in die vervoer tot by die kant van die pad lei tot ’n besparing

van tot R10.21 per siklus. Daar is bewys dat R tot ’n mate geskik is vir die simulasie van afsonderlike gebeurtenisse.

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1. Introduction

Background

With the introduction of mechanised timber harvesting operations rapidly increasing in South Africa, particularly in *Eucalyptus* pulpwood production, the most productive implementation of these systems is urgently needed (Hogg, 2009). Even though mechanisation is not new to the South African forest industry, there are still considerable inefficiencies in implementation as well as evidence of unnecessary operational variability (Hogg, 2009). This reinforces the need for the development of potentially best operating practices for industry concerning alternative work methods and different machine configurations which can lead to improved productivity and lower costs.

This thesis is concerned with the study of a common mechanised *Eucalyptus* pulpwood clear felling cut-to-length system, consisting of a combination of excavator-based harvesters and purpose built forwarders. The machines are studied individually and in relation to the system in order to gain a better understanding of the current work method, as well as attempt to improve each machine's productivity through changes to current operating practices using discrete-event simulation techniques. Simulation modelling has the ability to study effects of changes to harvesting from the safety of a computer without interfering with current operations. Results attained from the simulation can then be fed back into the real life system.

Objectives of study

The objective of the study is to analyse a typical South African excavator-based cut-to-length harvesting system working in *Eucalyptus* clear felling pulpwood production, in terms of productivity and cost using computer based discrete-event simulation. Additional and alternative simulation models will be developed with the aim of improving machine productivity and lowering the delivered cost per m^3. These alternatives will be compared with the current base-line system. All modelling is to be performed using open source software.

The following are sub-objectives of the study:

I. Determine the applicability of using open source software (R) for accurate discrete-event simulation modelling of forest harvesting operations.
II. Gauge potential machine work method optimisation and/or cost reduction using simulation-based operational adjustments.
III. Attempt to account for the impact of “high stand growth variability” on productivity and cost.

Scope of Study

The context of this study lies in the field of computer based simulated timber procurement of *Eucalyptus* pulpwood focusing on individual machine productivity and cost. The simulation models are built to include timber flow from the standing tree to a storage depot and include felling, processing (delimbing and debarking and cross-cutting) of trees, and the extraction of the merchandised assortments to the log storage depot situated beyond the compartment roadside.

2. Literature Review

Forest Harvesting operations

Timber harvesting is an integral part of silviculture and the first step in the renewal of a forest, while making wood available for use by society (Wakerman et al. 1966; Ackerman et al., 2012). Timber harvesting and transport costs constitute a large portion of mill delivered costs of wood. Therefore such operations must be carried out in the most efficient and cost-effective way possible (Ackerman *et al.*, 2012). In a typical South African cut-to-length harvesting operation, trees are felled, processed and then extracted to either roadside through primary transport or to a depot through extended-primary transport before secondary road transport to the mill.

Forest harvesting operation dynamics

During forest harvesting operations, the output of one machine is nearly always the input for the next machine in the system. Due to this fact, the operation of one machine affects not only its own productivity but also the subsequent machines in the system (Hogg, 2009).

As a result, the need to machine balancing, correct machine to site matching, as well as correctly sizing timber inventories has become more crucial (Hogg, 2009). Inventories between activities are crucial as they act as buffers to balance the interactions of machines making up the system (Asikainen, 1995). If inventories between machines or activities are insufficient, there will likely be adverse effects both up and down the value chain (Asikainen, 1995). These delays result in an increase of unproductive time which in turn leads to higher cost per unit of timber (Hogg, 2009). Insufficient inventories between activities are a problem but equally, oversized inventories can have a negative effect on timber harvesting operations as well. Oversized inventories can lead to decreased productivity, timber degradation and fibre loss (Asikainen, 1995).

Hogg (2009) stated that balancing of machines aims to bring the potential output of each activity within the timber procurement chain to as similar a capacity as possible, with the most expensive activities being the best utilised within the system. Balancing is achieved by assigning the correct number of machines per task according to machine capabilities and system demands (Hogg, 2009).

Randhawa and Scott (1996) noted that equipment selection in harvesting operations is affected by the harvesting environment, stand characteristics and transport distance. Other factors such as potential equipment interaction dynamics, timber volume to be extracted, required buffer levels and machine balancing all influence the appropriate selection of equipment (Hogg, 2009).

Modelling

Modelling is a broad term used to describe an entity, object or system in any form other than itself. During modelling, abstraction of the assumed real world from the real situation occurs by concentrating on the dominant variables that control the behaviour of the real system (Taha, 2003) (Figure 1). Models can be either prescriptive (used for systems that don’t currently exist) or descriptive (used for systems that currently exist) (Hogg, 2009).

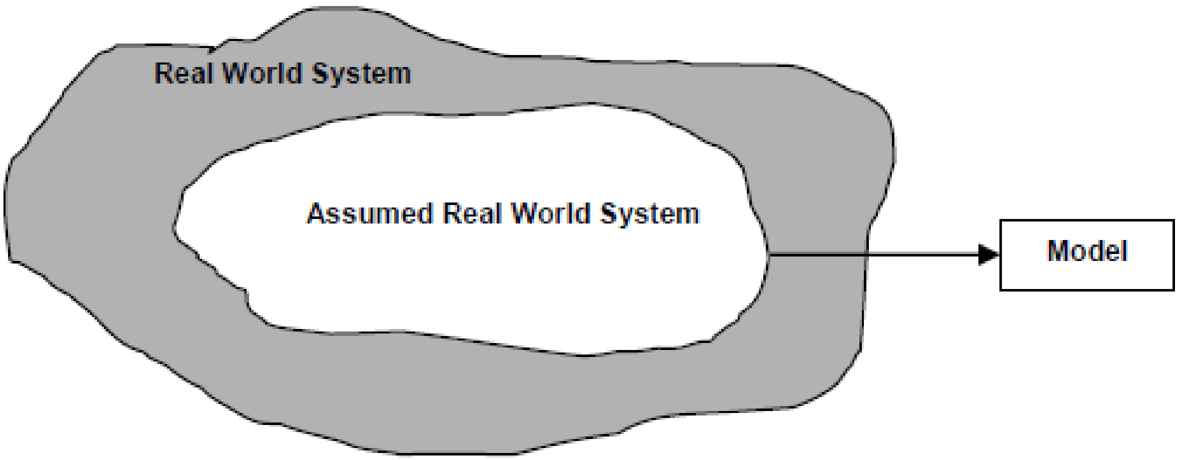

Figure 1: Model as an abstraction of reality (adapted from Taha (2003)).

Due to the model being an abstraction of the assumed real world system, the functions that it is composed of allow the model to represent the real world system to an acceptable degree of accuracy (Taha, 2003).

The degree to which a simulation model represents reality can be explained by two types of models namely; isomorphic and homomorphic models. Homomorphic models are similar to the real system in form but differ in fundamental structure, whereas isomorphic models can be described as having elements in the model that match the object exactly (relationships and interactions between elements are preserved in an isomorphic model) (Hogg, 2009). Simulations are homomorphic in nature and the degree of isomorphism (degree to which the model represents reality) has to be stated and tested before conclusions can be drawn from the model, this process is known as model validation (Banks, 1998).

Simulation

Simulation Defined

Operations research can be defined as a scientific approach to decision making that involves the operations of organizational systems (Hillier & Lieberman, 2010). The general approach followed when carrying out operations research is one of scientific method. In brief the process involves carefully observing and formulating the problem, and then developing a model that abstracts the essence of the real problem. The model is then studied to determine whether it is a sufficient representation of reality containing all essential features of the situation so that valid conclusions can be drawn for the problem at hand (Hillier & Lieberman, 2010). In general, the outcomes of operations research are to optimise a system (Hogg, 2009).

Simulation as well as queuing together form one branch of operations research (Taha, 2003). Simulation has been one of the most widely used operations research tools to date. Its popularity as an operations research tool stems from the ability to compile a wide variety of methods as well as applications in order to predict real world system behaviour through mathematical evaluation, often performed using software designed to replicate system processes and operations (Kelton et al., 2003).

Although there are many definitions of simulation, all the definitions revolve around the same core understanding that simulation is the re-creation of some real system process, followed by the modification of the system in order to understand it better, after which conclusions can be drawn. A clear to the point definition can be found in Banks (1998). He described simulation as being “The imitation of the operation of a real system or process, over time”. He further stated that during the process of simulation “an artificial history is created of the system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented”.

It is therefore evident that simulation can be seen as a tool in which a real system can be recreated and then observed over a required time frame in order to understand the system processes given the conditions of the model forming it. The behaviour of the system can then be related back to the real system represented by the model.

Although simulation forms a part of operations research, and operations research is often used to optimise a system, it should be kept in mind that simulation itself is not an optimisation technique, but rather a tool that can provide estimates of system performance through use of modelling (Hillier & Lieberman, 2010). It can be used to evaluate alternatives within a system, but there is no guarantee that system improvement will occur (Hillier & Lieberman, 2010).

Simulation application is generally used to analyse complex real world systems that analytical operations research techniques often cannot, these systems often contain complex component interactions. There are numerous built in parameters and functions that allow simulation to cope with these complexities (Hogg, 2009).

Simulation in perspective

The first simulation languages specifically designed to facilitate the programming of simulation models (GPSS, SLAM and SIMAN) were first introduced around 1961 (Asikainen, 1995). These languages formed the basis for model construction that resulted in simplified simulation implementation (Asikainen, 1995). Simulators succeeded simulation languages once computers had become more powerful. These simulators offered the benefits of graphical user interfaces that would allow uses to select and build models using pre-programmed statements (Banks et al., 1991). Simulators designed in the early 1980's focused primarily on modelling manufacturing processes, however, in the recent past simulators have now been created for a wider variety of processes outside of the manufacturing environment (Asikainen, 1995). It should be mentioned that programming, conditional routing, entity attributes, global variables and interfacing with other software are some of the favourable qualities associated with these programmes (Banks et al., 1991).

Simulation does not only consist of one type of model. Simulation can be classified according to the type of model produced by the process (Figure 2).

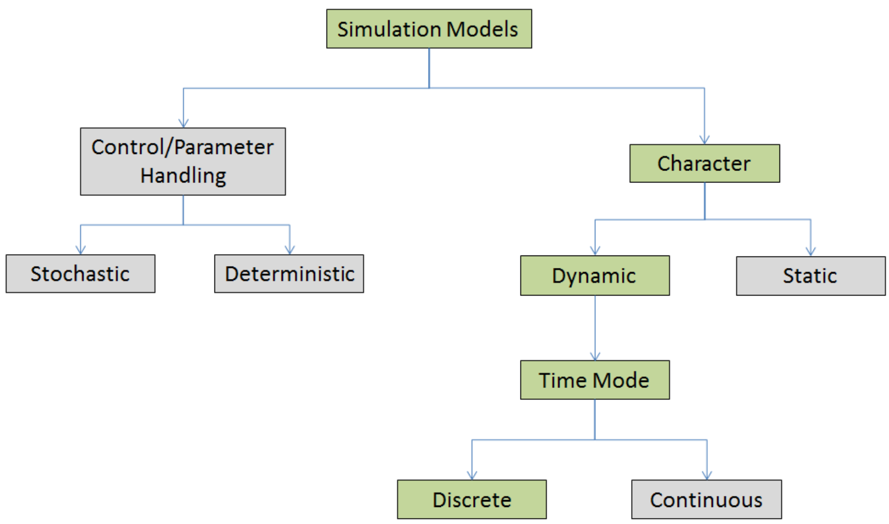

Figure 2: Breakdown of different types of simulation (adapted from Asikainen, (1995)).

Dynamic and Static Simulation

In a dynamic simulation time is an essential component of the process and is included in the process, while in static simulation time plays no part in the process and is not explicitly included (Kelton et al., 2003). Dynamic models represent a system as well as the way it changes over time. While static simulation represents a system at a specific point in time (Asikainen, 1995).

Stochastic and Deterministic Simulation

Stochastic models involve the random generation of numbers (probability distributions, random number generators) as input during the simulation process. Due to this attribute stochastic simulations can often produce results that differ to that of the real world data. Stochastic simulations can also generate a different set of results per repetition run. Deterministic models have no random data inputs, i.e. the input data will always give the same output and return the same output for multiple repetitions (Asikainen, 1995), often falling into the class of heuristic programming.

Continuous and Discrete Simulation

Continuous models can be described as models that describe that state of the models as it changes over time with state variables constantly changing (Asikainen, 1995). In discrete models the state variables change instantaneously at a finite number of points in time due to certain discrete occurrences also known as events (Asikainen, 1995). Event points are linked as time moves forward and time between events are defined by the activity's duration. During simulations, software scans the model for conditions of starting or ending an activity. Once a prescribed condition is met the activity is carried out that instant representing a discrete point or event (Hogg, 2009).

Application of Simulation

Simulation has many uses but some of the most common uses for simulation include (Kelton *et al.*, 2003):

- Measure and improve a systems performance, even if it does not exist yet.
- Test "what if" situations or unplanned situations along with their effects on the system.
- Evaluate alternatives within systems and the effects of using these alternatives.
- Providing detailed information for understanding complex systems and operations.

Figure 3 illustrates how system production could potentially be improved through use of simulation.

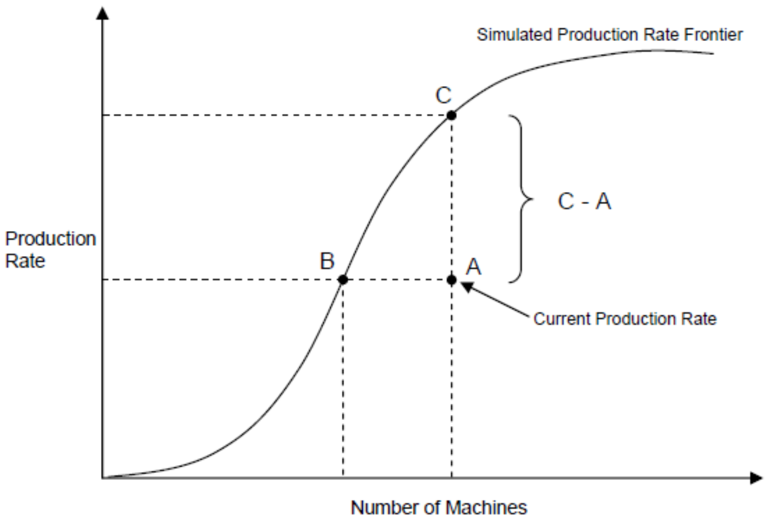

Figure 3: Hypothetical production rate of a simulated forest harvesting system (adapted from McDonagh (2002)).

The current harvesting system (Figure 3) is operating with a production rate indicated by point A. However a simulation study performed on the system shows that the system could in fact produce at a production rate equal to point C. It can be deduced that the current system is under-performing by the difference between C and A. Another point that could be made is that, if the number of machines is the only productivity determining factor, according to the simulation results the number of machines could be reduced (B) while still yielding at the same production rate but have a lower system capital cost (McDonagh, 2002). It should be noted that the simulation production frontier and the optimal real world system production frontier might not be equal. This is mainly due to the process of systems improvement being carried out on a trial and error basis by the user (Goulet et al., 1980).

It should again be pointed out that simulation is not an optimisation tool but rather an analysis and alternative scenario testing tool which often leads to system optimisation. This point can be seen when again looking at the simulated production frontier curve (Figure 3). Although point C is the simulated optimum, the actual optimum production rate may lay somewhere higher than point C however, point C is closer to the actual optimum production figure than the original system operating at point A: i.e., the use of simulation allows the point C to be discovered.

Advantages and Disadvantages of Simulation

Simulation and modelling like all other software and operations research techniques have certain advantages and limitations. Below is a general list of advantages and disadvantages gleaned from literature.

Advantages of simulation:

- Long periods of time can be modelled in a short space of time through simulated time compression. This allows quicker data collection and keeps costs down as well as promotes efficiency (Ziesak *et al.*, 2004).
- Able to create and test alternative scenarios without disrupting the real world system (Asikainen, 1995).
- Able to study and experiment within a modelled version of a real world system without causing delays, additional costs or in situations where direct real world system experimentation is not possible (Asikainen, 1995; Ziesak *et al.*, 2004).
- Proposed real world systems can be experimented with before their construction begins to determine potential threats and problems that may arise. This again promotes efficiency as well as lower system start up times (Kelton *et al.*, 2003).
- Experiments to the system are often better controlled when performed in a simulation versus experimenting with the real system directly (Law & Kelton, 2000).

Disadvantages of simulation:

- Each simulation has to be tailor made to the specific system being modelled; therefore the results can often not be applied to other scenarios (Ziesak *et al.*, 2004).
- The quality of the model as well as the accuracy of the input data determines the analysis quality. Inaccurate results may be generated which can negatively affect the real world system (Asikainen, 1995; Hogg, 2009).
- Collecting quality data can be expensive and time consuming (Nelson, 2003).
- Validation and verification of the models can be a lengthy and tedious task (Nelson, 2003).
- Detailed simulations can be expensive and time consuming, especially the data collection and model construction phases of the project (Asikainen, 1995; Law & Kelton, 2000).
- Simulation software is often expensive (Hogg, 2009).

Simulation terminology

A simulation is constructed using multiple components which ultimately determine the nature of the simulation outputs. Many simulation programmes have some form of menu based component selection. R (R Core Team, 2014) on the other hand does not. Each component needs to be created through coding a specific function. However, the components of a simulation are still evident. Kelton *et al.* (2003) provides a clear definition of some of the components found in simulations.

- Entities: These are individual units (dynamic units) that flow through the system, usually created when entering the model and are disposed of when exiting the model. An example of entities within the study presented in this thesis would be the individual trees or timber stacks.
- Attributes: As the word suggests, attributes are characteristics of an entity and each entity may have different attributes. An example of this would be the individual tree volume.
- Variables: Also known as the global variables or state variables are instantaneous measurements of specific characteristics of the system. These

variables can change over time and apply to the system as a whole. An example could be the number of trees within a harvester's boom reach limits.

- Resources: These are units which change the shape, form or state of any entity in the model. This would be the harvester for example.
- Statistical accumulators: Are counters that measure intermediate statistical variables within the model as the simulation progresses for example, counting the number of trees that the harvester has felled.
- Event: An occurrence that takes place at an instant of simulated time. An event may alter the state of the system by resulting in a change of attributes, variables or statistical accumulators. Models in discrete-event simulation are centred on these events.
- Process: A process is made up of an entity using a resource, delaying it for a specified period before releasing it again. Entities are then in some way changed after being processed.

A resource waits for an entity to seize it. Processing of an entity therefore incorporates the entity seizing the resource, holding it for the time required to transform the entity in some way and releasing the resource in order for the next entity to utilise it. This is the manner in which entities flow through the model or the entity to seize the next resource (Hogg, 2009).

Data acquisition and incorporation

In order for a discrete-event simulation model to accurately represent reality, data pertaining to the observed system is needed such as time consumption of activities within the current system. This data is used as input into the simulation models and will determine the outcomes of the simulation. One of the most important concerns that must be addressed by a simulation is the ability to accurately identify and model probability distributions of input data. A second condition is that the simulation programme should maintain the correlation between variables in these original data distributions (Taylor et al., 1995). As mentioned under the disadvantages of simulation, the data that is used as input into the simulation will ultimately determine the quality of the output results as well as the ability of the simulation to accurately represent the real system (Asikainen, 1995). A potential threat to the quality of the data comes in the form of the problem when the system being analysed has no collectable data. Alternative methods must then be used to obtain data concerning these systems but the data credibility will vary according to the data collection method used (Hogg, 2009).

Common sources of data available for collection

When data are collectable regarding a system some of the most common sources are listed below:

- Previous studies or statistics (Asikainen, 1995). Studies previously carried out on similar systems can provide data for new studies. The data that is obtained may be out dated though.
- Data can be derived from existing reports (Asikainen, 1995).
- Data can be collected through system observation (Kelton *et al.*, 2003). Physically studying the system can generate suitable data. However, the data gathered only applies to the system studied under the conditions that the system was exposed to at the time of observation.

If data is collected for a study it can be incorporated into the simulation through one of two ways. Either though empirical distributions or through theoretical distributions (Kelton *et al.*, 2003). Empirical distributions are used when no theoretical distribution can be fitted to the data. The distribution will only generate values within the range of the observed data and requires greater amounts of computer memory than theoretical distributions would. Theoretical distributions use a smooth curve to generate values, some of which may fall outside of the real world observed data range. Using theoretical distributions has one advantage in that they allow reproduction of random observations within the model (Hogg, 2009).

Common sources of data when data are not available for collection

When data are not collectable, some form of data generation will be necessary. Asikainen (1995) recommends that when using data produced via data generation, it should be stated that the input data are only estimates when presenting results. A disadvantage to using data generation can be found during the validation of the models used in the simulation, as there will be no real system data to benchmark against.

If real data cannot be collected the following methods are often used to obtain data:

- Estimates and educated guesses (Asikainen, 1995).
- Manufactures may give information on the performance level of new/modified machines. If the operation of comparable older machines is known, the effect of modifications can be tested (Asikainen, 1995).
- Theoretical considerations (Kelton *et al.*, 2003).

Random number inputs and observations

The main aim of computer simulation models is to imitate the behaviour of real world systems over time through use of numerical evaluation (Asikainen, 1995; Law & Kelton, 2000).

Taylor *et al.* (1995) explained the logic behind dynamic stochastic simulations in that if the probability distribution for each activity's time expenditure is known, random observations can be drawn from the random probability distributions and then joined together to describe the systems operation over time. In order for the simulation to generate random observations, random values must be created within the model.

Most simulation programmes have built in random number generators. These random number generators produce random number streams during the running of the simulation. The random number streams allow the combination of user-defined probability distributions with random numbers in order to generate artificial observations and in the process imitate real world randomness (Hogg, 2009). To eradicate bias from the model, the random number stream has a seed value which when changed, produces a different stream of random numbers. Changing the seed value every replication can ensure independent unbiased observations (Baumgras *et al.*, 1993).

Model validation and verification

The problem of trying to determine the accuracy of a model to represent a real world system is one that often plagues researchers (Asikainen, 1995). A valid model gives a good representation of reality; however, it should be kept in mind that a model is only an abstraction of reality. Model verification and validation are two methods to ensure that the model represents reality to a suitable degree. Model verification refers to the process of debugging the simulation; verification involves the debugging of the simulation while validation refers to the tests performed to ensure the simulation represents the real system accurately (Asikainen, 1995).

During the model verification process the simulation is checked to see if any programming mistakes have been made (Asikainen, 1995). The results of the real system can be manually calculated and then compared to the output of the simulation, or for simulations larger in size a more complex approach may be needed. The process of verification for complex simulations is called tracing (Asikainen, 1995). During this process the simulation is checked in steps and the value of parameters or variables are generated and displayed immediately when the event occurs effectively running the model step by step and displaying each step's output (Asikainen, 1995).

The ideal method to ensure high model validity is to develop a model with "high face" validity (Asikainen, 1995). To develop such a model, the modeller should make use of all existing knowledge; i.e., discussions with experts and observing the system in detail. Through conversation with experts in the field of the system it will ensure that the model will not be too abstract and will in fact represent the real system effectively (Asikainen, 1995).

About the software: R

The software used in this study is R (R Core Team, 2014). R is an open source software package for statistical computing and graphics. It is part of the GNU project (GNU is a reverse acronym for GNU's Not Unix, GNU is a Unix-like system that is free software.) which shares similarities to the S language and environment. R provides a wide range of statistical techniques such as (but not limited to) linear and non-linear modelling, classical statistical test and time-series analysis (R Core Team, 2014).

R like S is designed around a true computer language. It allows the user to increase functionality by adding new user defined functions. For computationally intense tasks, R can be linked to the languages C, C++ and Fortran which can be called at runtime. R gives the user the ability to use the C language to manipulate R objects directly (R Core Team, 2014).

The R environment can be used for a multitude of tasks outside of plain statistical computation through the use of “packages”. Packages are collections of R functions, data and compiled code in a well-defined format (R Core Team, 2014).

A benefit to the flexibility of R is the ability to combine the numerical output generated with graphics. Although complex, simulation graphics can be generated. A graphical representation of this study was not created in full due to time constraints. R can also be linked with other software such as geographic information systems (GIS). For example by importing shape files into R, spatial analysis linked to the actual site can now be performed.

Traditionally simulation software often favours a factory type setup, where the entity would move through the various processes and then exit the system. However when simulating a harvester, it is the process that moves to each entity and then interacts with the entity. This is often difficult to perform using conventional simulation software.

Simulation of forest harvesting operations

Applicability of simulation to forest harvesting operations

Computer simulation of forest harvesting operations has been occurring since the late 1960s (McDonagh, 2002).

McDonagh (2002) compiled a list of previous as well as existing simulation models that had been created from the late 1960s until 2001. These models were developed in the USA, as well as in parts of Europe. Most of the models in the list studied forest harvesting systems as a whole and attempted to improve efficiency of the systems whereas other models focus more on individual machines and their optimal use within the system. Eliasson and Lageson (1999) used a deterministic simulation to simulate a single-grip harvester working in a thinning operation. The authors went on to state that the simulation should accurately model the motions of a real harvester and must interact with the environment.

Simulation has also proven to be a useful tool in analysing harvesting systems and identifying bottlenecks in the primary stages of wood delivery (Talbot et al., 2003). Talbot et al. (2003) used a stand-level simulation in order to study the relative performance of two integrated harwarder machines. Talbot and Saudicani (2005) performed a study using discrete event simulation on the productivity, cost and fuel-consumption rates of two wood-chip production systems.

Asikainen (2001) simulated a barge logging system in order to compare alternative work methods and machine combinations within the system. Using simulation for the study of a barge-based system had the advantage of being able to quantify machine interactions such as queuing, as these play a vital role in waterway transport systems (Asikainen, 2001).

Wang et al. (1998) used an interactive simulation in order to determine potential interactions of stand type, harvesting method and equipment. Wang et al. (2005) used simulation to model in detail a cut-to-length harvesting operation working in Appalachian hardwoods. Data collected during previous studies was used as input data for a 3D stand generator, whereas the machine processes where programmed through numerical models and pre-defined machine trails. Wang et al. (2005) went on to state that without simulation, the analysis and comparison of alternative stands, travel routes, traffic intensities and machine configurations simply would not be possible. Wang and Greene (1999) used an interactive computer simulation to model forest stands as well as the operation of machines within these stands.

Hogg et al. (2010) using discrete event simulation performed in Arena 9 analysed a typical multi-stem harvesting operation in South Africa. The study was aimed at using simulation to test alternative machine combinations in order to improve the system’s potential productivity. Belbo (2010) used simulation to study the effects of two different working methods on harvester productivity. This study was performed in a similar manner to the one presented in this study. The simulation was carried out in R.

Ghaffariyan et al. (2012) studied a mechanised cut-to-length operation in New South Wales, Australia. Elemental times gathered through time studies were used to generate productivity models, although the study was performed on *Pinus radiata* the study yielded similar results to the results of the study presented in this thesis. Inberg et al. (2002) used simulation to determine a dynamic model to model boom movements, more specifically boom tip acceleration and trajectory during crosscutting by a single-grip harvester.

Spinelli et al. (2009) used simulation to simulate a cut-to-length and whole-tree harvesting systems. Various simulations where then run in order to determine which of the two systems was cheaper and more productive. From the results of the simulations, productivity models were then generated that were based on tree weight.

Väätäinen and Lamminen (2014) used an interactive simulation developed by Ponsse in order to test the effects of various forwarding techniques on productivity. This was done by changing; travel directions, load combinations and operators. Väätäinen et al. (2006) used discrete-event simulation to determine cost-effective harwarder working patterns for forest harvesting contractors in different logging conditions.

Perhaps the most relevant statement regarding the use of simulation in forestry, specifically for plantations used for pulp and paper industry, can be found in Hool et al. (1972). Hool et al. (1972) was quoted as saying “Pulpwood systems are too complex to visualise easily, respond too slowly to perturbations and are too expensive to experiment with. Consequently simulation is particularly applicable”.

It is thus clearly evident that computer simulation has been widely used within the forest industry and has cemented a place in the study and analysis of new and existing forest harvesting systems.

Commercial simulation software in forestry

Asikainen (2001) and Hogg (2009) were able to successfully simulate forest harvesting operation as well as alternatives to the system through use of a commercial industrial manufacturing simulator namely Arena simulation software. Asikainen (2001) went on to say that this simulator suited the application of simulating barge operations. However, model construction was often described as labour intensive. In the study by Talbot and Saudicani (2005) the statistical package SAS was used for the running of the simulation of the wood-chip production systems. Talbot *et al.* (2003) also used SAS to simulate the two integrated harvester/forwarder concept machines.

Although there are many forms of commercial simulation software available there are some limitations to using this software to simulate forest harvesting operations. A list of limitations when using commercial simulation software in forest operations can be drawn up from Ziesak *et al.* (2004):

- Forestry works on a much larger scale than most industrial facilities.
- There are far more parameters in forestry models due to the scope and complex nature of forest harvesting operations.
- Harvesting operations are mobile, as machines move through stands and the stands themselves change as machines move through them and to new stands.
- Machine movements are quite specific and even though sometimes are seen as unconventional they are determined by the system and the operation thereof.
- Harvesting systems often contain complex logic rules which differ vastly from those of industrial production.

Taking into account the above mentioned limitations, Ziesak *et al.* (2004) as well as Hogg (2009) concluded that simulation software designed for the industrial manufacturing industry can be applied to the field of forest operations.

Simulation model classification for Forest harvesting operations

Randhawa and Scott (1996) state that two resource analysis simulation models in forest harvesting operations can be classified into either phase models or tree-to-mill models.

Asikainen (1995) went on to define tree-to-mill simulation models, as models that focus on the entire process: i.e., from felling at the stump up until the tree arrives at the mill. These models aim at improving the system as a whole by improving machine operating techniques and interactions between machines, as well as minimising bottlenecks (Hogg, 2009).

Phase models focus on a specific part of the harvesting process. They do not consider the harvesting value chain and the potential implications that could be incurred along the value chain as a result of changes to a machine's operating practices. These potential implications fall outside of the study scope. Figure 4 is a graphical representation of the different simulation models; the single machine model path (highlighted in green) is the path chosen for the study presented in this thesis.

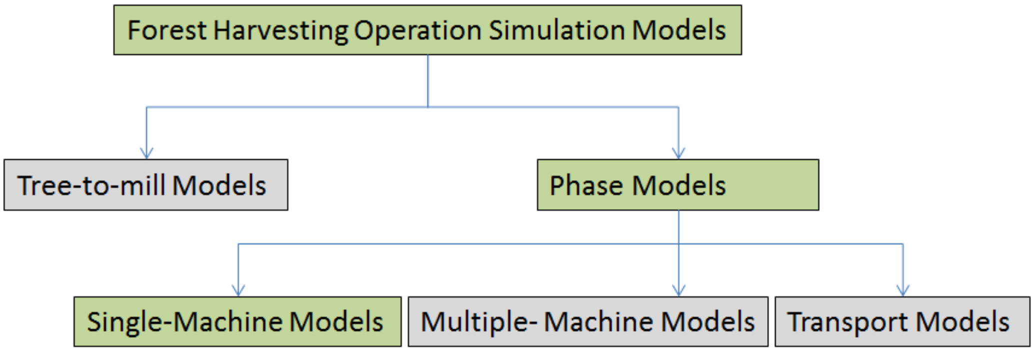

Figure 4: Two main types of forest simulation models (adapted from Hogg, (2009)).

3. Methodology

Research area

Data collection for the study took place in the vicinity of Richmond located 43 km SW of Pietermaritzburg in KwaZulu-Natal on Mondi Forest's Nicholson farms' compartment B008, at coordinates 29°52'29.43"S 30°16'39.28"E (Figure 5). Compartment B008 is situated at an altitude of 900 m above sea level (Braithwaite, 2013). The area's mean annual precipitation (MAP) is 852 mm, most of which occurs during the mid-summer months. Mean annual temperature for the area is 25.2 °C (Braithwaite, 2013). The study area was located on relatively flat ground, with slope ranging from 0% up to 3%.

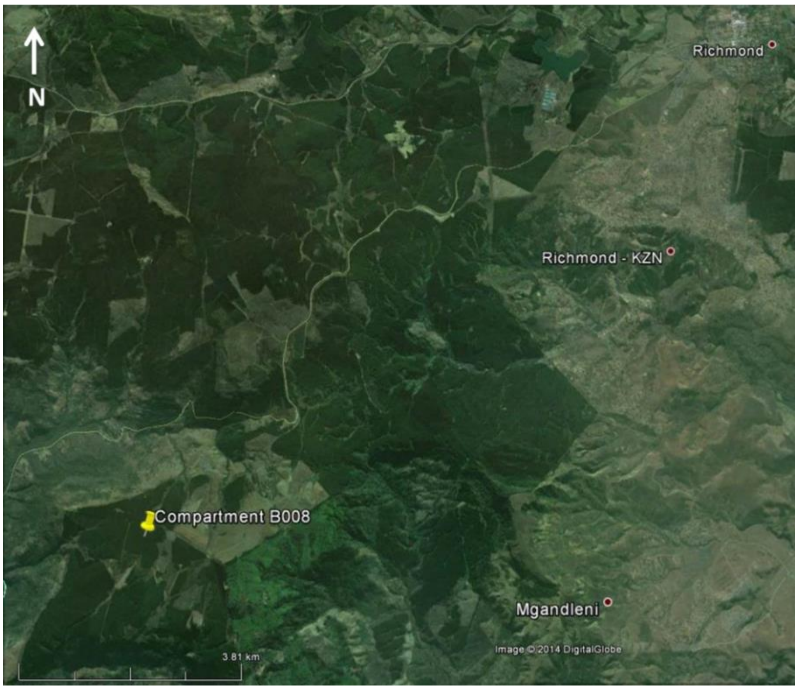

Figure 5: Google Maps image of the location of the study site.

The compartment comprises of 7-year-old *Eucalyptus smithii* trees at time of felling. Tree heights and diameter at breast height (DBH) varied due to poor planted stock, as well as a large percentage of the trees having broken tops. The compartment was planted at a spacing of 3 m x 2 m (1 106 stems ha^{-1}). The compartment has forest roads located on both the south-western and north-eastern boundaries (Figure 6). The storage (depot) area is located 497 m away from the furthest stack (Figure 6).

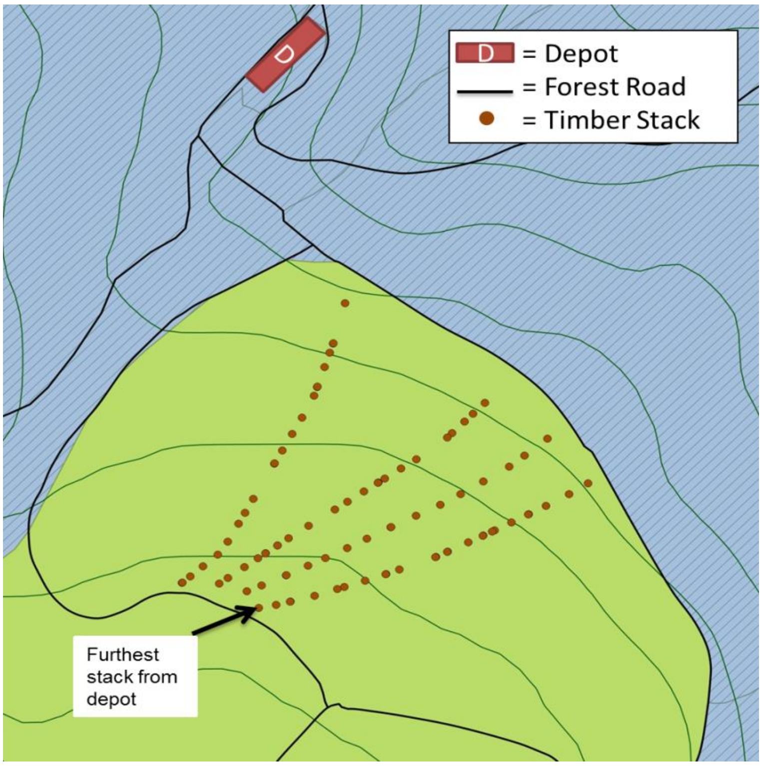

Figure 6: Compartment map showing location of forest roads and timber stacks.

Compartment B008's basic data is as follows (Table 1).

Table 1: Basic tree information.

Compartment parameters	Measure
Mean DBH (cm)	15.9
Mean Height (m)	17.4
Mean Stem Volume (m^3)	0.14
Volume per Hectare (m^3 ha^{-1})	154.8

E. smithii has a reputation in South Africa for having poor stem form, and the trees in the study area were no different. Butt sweep was a common occurrence, as was forking higher up the stem most likely as a result of snow damage. The site was selected as it is a common occurrence in South African forestry to have sites of poorly formed trees, often drought stressed, with wide individual tree volume variances. However, these sites are often not used for productivity studies. The machine operators had at least two years' experience on the machines studied. The contractor had been previously involved in a pilot study and was aware of the significance of the study.

Soil information

The dominant soil type is the Kranskop form of the Fordoun family, known as Kp 1100 (MacVicar, 1991). The soil is described as having good drainage properties despite having relatively high clay content (Kuenene *et al.*, 2012). The study was completed during dry weather so the soil type did not influence the outcomes.

Harvesting system selection and study

The study focused on modelling an existing mechanised cut-to-length harvesting operation. A feature that distinguishes this study from others performed in Europe is tree stems are to be completely debarked before delivery to the pulpmill. Trees are felled, processed (debarked and debranched and crosscut) by the harvester before being extracted to a depot area using a forwarder. The machines were modelled individually using data collected from intensive time studies. Alternative work method scenarios were virtually created using the current operating practices as the base-line. Alternative scenarios comprised of the same machines, however each machine performed an operational task in a different manner to the observed work method. All scenarios were modelled in R (R Core Team, 2014).

The following are scenarios modelled in this study:

I. Scenario 1: Current harvesting operation.

II. Scenario 2: Harvester felling either 4 or 5 tree rows or in combination per swath, where a swath is defined as a collection of tree rows running the length of the compartment that are within the reach of the harvester's boom. Forwarding was excluded from this scenario.

III. Scenario 3: Harvester felling larger sized trees (0.2 m^3 and 0.3 m^3 trees) and forwarder extracting the expected larger log assortments. The forwarder is modelled with the original sized grapple (0.8 m^2) as well as larger grapple (1.0 m^2).

IV. Scenario 4: Forwarder incrementally extracting timber up to a maximum distance of 1000 m using original forwarding pattern, making use of both roads on the south-western and north-eastern sides of the compartment to the log storage depot. The forwarder is modelled with both the original sized grapple as well as larger grapple. The harvester operates as specified in scenario 1.

V. Scenario 5: Forwarder incrementally extracting timber to a maximum distance of 900 m using only the north-eastern road. Forwarder modelled with the original sized grapple as well as larger grapple. The harvester operates as specified in scenario 1.

Current system

The current system comprised of the following equipment:

Two Hitachi Zaxis 200 excavator based harvesters with Maskiner SP 591 LX heads, and one TimberPro TF 840-B purpose built forwarder fitted with a 0.8 m^2 Matriarch grapple (Figure 7 and Figure 8).

Figure 7: Hitachi Zaxis 200 harvester in compartment B008.

Figure 8: TimberPro Tf 840-B forwarder in compartment B008.

The observed system used two 9 h shifts. The first shift starts at 5 am and ends at 2 pm. The second shift begins at 2 pm and continues to 11 pm. Refuelling and daily maintenance was performed once at the start of each shift. Lunch breaks were not strictly adhered to and operators would generally stop for lunch/tea breaks more than once per shift but for relatively short periods, normally <15 min per break. In total lunch/rest breaks added up to between 30 - 45 min shift^{-1}. The crew worked six days a week (Monday to Saturday).

An overview of both the harvester and forwarder work method is as follows. The harvester would fell, process (delimb and debark) and crosscut 10 trees per setting (five rows across by two rows deep), while straddling the third row of trees (Figure 9) effectively covering a 12 m wide swath (by straddling the third row of trees there are 2 rows of trees either side of the machine each with a spacing of 3 m between rows). During processing stems are fed through the harvester's head between 3 and 5 times with the last pass occurring during crosscutting. Crosscut log assortments are stacked to the left of the machine. A harvester setting is defined as the position of the machine between moves in a swath. The harvester creates a new stack of log assortments for every harvester setting.

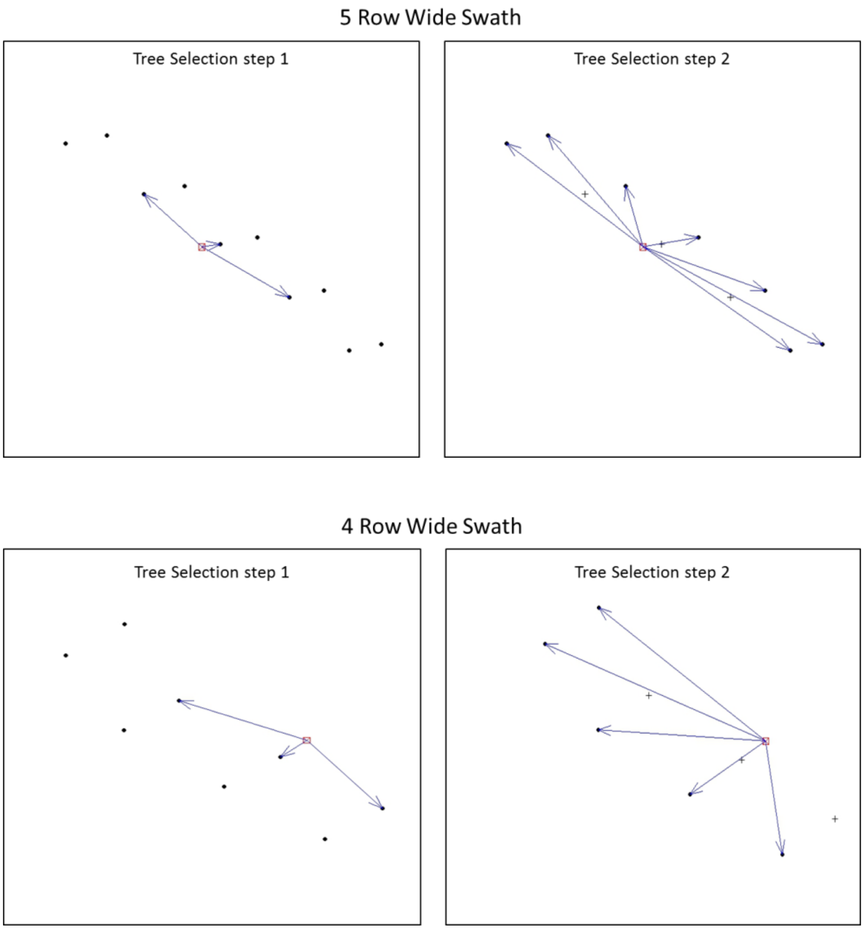

Figure 9: Harvester tree selection steps for both swath sizes.

On reaching the opposite side of the compartment the harvester turns and fells, processes and crosscuts trees into log assortments in a swath four tree rows wide. The harvester straddles the second row of trees from the right of the swath that the machine is working in (Figure 9). The harvester thus covers a swath 9 m wide and fells eight trees per setting (four rows wide by two rows deep). Log assortments are stacked to the left of the machine and placed onto the log assortment stacks created when felling the previous and adjacent swath. This is commonly known as double stacking. In this case the harvester has to reach 6 m to the left of the harvester when crosscutting the timber onto the existing stacks of log assortments. The harvester continues in this pattern until it has felled and processed all the trees in the study area. During the study, a total of four rows of stacks were created consisting of 89 stacks (Figure 6). The harvester crosscuts the stems into 5 m lengths.

The log assortment stacks are forwarded to the log storage depot two days after felling and processing.

Forwarding commences with the forwarder travelling from the log storage depot area, accessing the felling area via the road along the south-western edge of the compartment (Figure 10), travelling along the routes used by the harvester during harvesting.

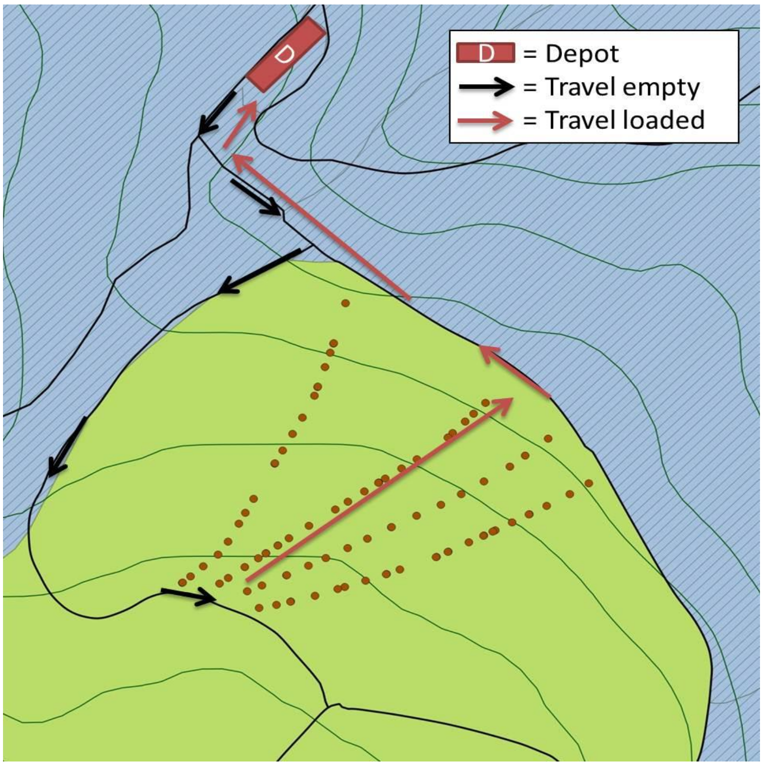

Figure 10: Observed forwarder travel direction.

Log assortment stacks are loaded from the left side of the forwarder onto the forwarder bunk. The forwarder make use of a process known as “indexing”, during which the forwarder operator flips the grapple full of timber vertically and taps it against the ground in order to “index” the load on the forwarder. This allows for the forwarder’s bunk space to be used more effectively. This process is repeated until an individual stack is loaded. The forwarder then moves to the next stack and repeats the loading process until the forwarder bunk is fully loaded. The operator then completes a production sheet specifying the time and load number, a process that is considered to be a delay for the purposes of the study.

The forwarder then returns either in the direction it has entered the compartment from or continues through the compartment until it reaches the road on the north-eastern side of the compartment. It then travels down the road until it reaches the log storage depot area and offloads the assortments. The log storage depot area is a centralised landing created along the forest road where forwarder loads are accumulated to be loaded onto the timber trucks at a later stage. At this point the operator again completes a production sheet.

System observation

The time studies were carried out from the 22nd June 2013 until the 5th July 2013. Machines were observed for entire shifts in order to reduce bias with regards to the operator's performance at a certain time of day.

Work elements and breakpoints

Work cycles are split into work elements, separated by breakpoints. Time consumption for a work element consists of the time between one breakpoint and the following elements breakpoint. Work elements and breakpoints used in this study are presented in Table 2 and Table 3:

Table 2: Harvester work elements and breakpoints.

Element	Breakpoint
Boom-out	Moment boom swings out after crosscutting until the head touches the next tree.
Fell	Moment head touches the stem until the tree begins falling.
Boom-in	Moment tree starts falling until the feed rollers begin to turn.
Process	Moment feed rollers start to turn until the final log section is cut and boom starts to swing out.
Move	Moment the machine moves until the moment the tracks stop turning
Delay	Moment any non-productive element begins until the machine begins a productive work element.

Table 3: Forwarder work elements and breakpoints.

Element	Breakpoint
Travel on-road empty	Moment forwarder starts moving at depot until the time it leaves the road surface and enters the compartment.
Travel off-road empty	Moment the forwarder enters the compartment until the time it stops next to a stack.
Load	Moment the forwarder stops at a stack until the moment the forwarder begins movement.
Travel between stack	Moment the forwarder begins movement until the time it reaches the following stack and stops movement.
Travel off-road loaded	Moment the operator has finished recording the load details until the time the forwarder leaves the compartment and enters onto the road surface
Travel on-road loaded	Moment the forwarder enters onto the road surface until the moment it stops at the depot.
Unload	Moment the forwarder stops at the depot and the boom moves towards the bunk until the last grapple load of timber has been placed on the stack.
Delay	Moment any non-productive element begins until the machine begins a productive work element.

Data collection and preparation

As previously mentioned, data collection was carried out through time studies in an area clear of obstructions and severe changes in slope. All the trees within the study area were sequentially numbered. Each tree has a row number assigned to it. The row number corresponds with the row number of that tree observed during the time study. Each trees' DBH (cm) and height (m) was measured and recorded using a diameter tape and Laser Vertex respectively. Once all trees had been marked and measured the harvester began felling and processing the trees. Timing of the harvester was carried out using a handheld Trimble GPS with WorkStudy+ software (Quetech Ltd, 2012) installed. The software allows user-defined breakpoints, which are selected every time the relevant breakpoint is observed during the operation. Element times are recorded in centi-minutes and the method of timing is known as snap-back timing (Kanawaty, 1992). The snap-back timing method allows each work element to be measured individually from zero time until completion of each work element.

In addition each stack of log assortments created by the harvester was assigned a unique number and all accessible log diameters at both thick and thin ends measured. Corresponding log lengths were also recorded. Distances from the road edge to the first stack in each row as well as the distance from the last stack to the lower roads edge was measured with a tape measure (Figure 11). The distance from the middle of each stack to the middle of the following stack was then measured using a measuring tape (Figure 12).

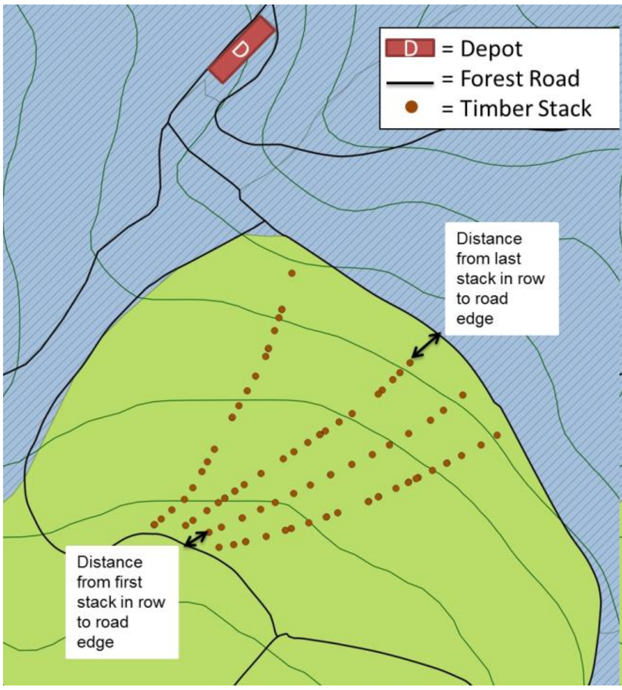

Figure 11: Example of measuring the distance from first stack in a row to the road edge and last stack in a row to road edge.

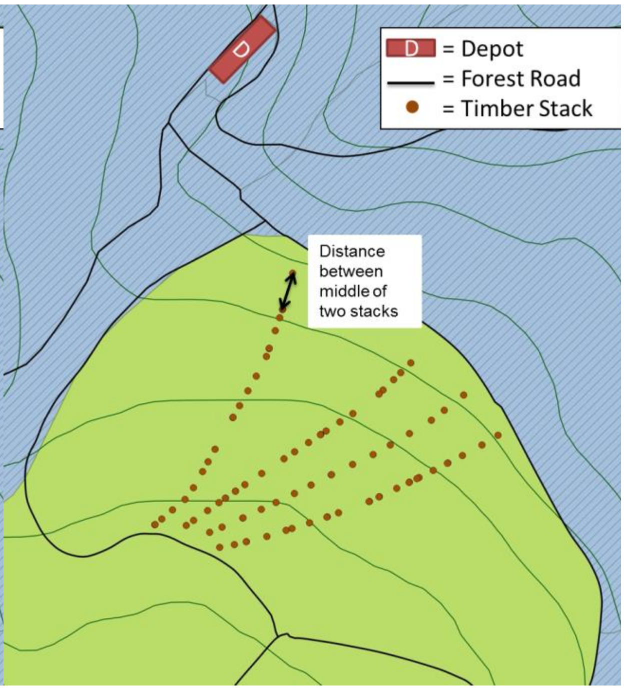

Figure 12: Example of measuring the distance from middle-middle of two stacks

Data collection for the forwarder was done in a similar manner to that of the harvester. The forwarder extracted log assortments out of the stand to the log storage depot. Additional forwarder positional data was collected using a Multidat GPS (Castonguay Electronique, 2006) tracking unit mounted in the cab of the forwarder. The Multidat records the paths along which the forwarder travels at predefined intervals of 50 m or when the accelerometer within the Multidat detects acceleration of the machine above 1 km h^{-1}. This positional data is used to identify actual travel routes and distances travelled along these routes.

Field data is then exported into Microsoft Excel spread sheets. The data is flattened. A process in which a complex table of data is simplified by organising the table into a two-dimensional format consisting of field information (tree number, stack number or work element) placed into one column and the corresponding information (work element times, tree volumes or stack volumes) placed in adjacent columns. This flattened format is required by R.

Processing and crosscutting work elements are grouped for the harvester. This is necessary, as during the time study the harvester operator does not always zero the crosscut saw before beginning crosscutting. It is therefore impossible to observe a clear breakpoint between the processing (debarking and de-branching) and crosscutting work elements.

The forwarders data requires no alteration and no elements need to be combined. Log stacks are assigned their respective row number. The data sheets for the forwarder are then flattened. Once all data (both harvester and forwarder) are flattened in Microsoft Excel it is saved in CSV format for importation to R.

Once the data sets are imported into R they are subset; in other words, filtered by work element in order to obtain work element times for each individual work element. This is done using R software's "plyr" package (Wickham, 2011). These subsets are then used to obtain the theoretical distributions for each work element. The data is first run through Input Analyzer (Rockwell Automation, 2012) software that is able to fit a list of various distributions to the data set and determine which theoretical probability distribution fits the input data best. This method was used by Hogg (2009) for the same purpose.

By using the summary output of the Input Analyser software as the baseline, the theoretical distributions are now fitted using the built-in R functions found in the "MASS" package (Venables & Ripley, 2002). These functions are capable of fitting a specified theoretical distribution to the subset data. Input Analyser and R do not contain the same number and type of distributions. In cases where the best fitting distribution according to Input Analyser is not available in R, the next best fitting distribution according to Input Analyser is used. The best fitting distributions can be found in Table 8 and Table 9.

Ideally linear models based on the forwarder's travel distance would have been better suited to the data that was collected, however, the linear models created indicated large amounts of variation. This variation led to low R^2 values for all forwarder travel models. This problem could be overcome through calculation of the forwarder's speed on the different road segments and then using the calculated speeds as input variables into the linear models (Table 11).

Spatial model construction

Spatial components of this study are carried out using QGIS (QGIS Development Team, 2013) open source GIS software. Some spatial components require a few assumptions that may not necessarily be true for the study area in question, but were used to simplify some problems encountered. These problems include areas of missing trees and the possibility that the virtual trees and log stacks may not be in precisely the same location as in reality.

Timber stacks are first plotted on the compartment shape file layer using the physical measurements from the field study. This is done by using shape files of the compartment with the study area marked out. Points that were recorded using the Multidat were then plotted on top of the compartment layer. By using the physically recorded distances, photos and the forwarder's travel path data from the Multidat, features were added to the shape file representing log stacks.

Four rows of stacks are produced, with each containing the same number of stacks that were observed during the time study (89 stacks in total). Each row was plotted on the left side of the forwarder's travel path. The newly created stacks had their coordinates captured. The stack number and their corresponding coordinates are then saved to a new Excel spread sheet where they are saved in a CSV format.

A similar process was carried out for the creation of the virtual trees to be harvested. Using the compartment shape file, the forwarder stacks were plotted again. Through photo evidence it could be seen that the harvester operator would create the log assortment stacks along the first row of the swath (furthest row to the left). Features representing trees were then overlaid at a fixed spacing of 3 m x 2 m. This created a virtual five row wide swath of trees. The same process was performed to generate a four row wide swath of trees but only four features representing trees were placed alongside each other in the shape file. After the trees have been plotted the log stacks are removed from the shape file layer.

The virtual swaths are then duplicated until the study area is populated with virtual trees. There were mortality issues with the real stand and it became too complex to determine which trees to remove from the virtual stand to replicate this, therefore a few assumptions are necessary.

Study assumptions

With regard to the virtual generation of the stand and stacks, it is assumed that both the tree positions and the stack positions remain the same for each replication of the simulation. Tree mortality is not represented in the stand generation itself but is accounted for using differing amounts of trees per swath. The virtual swaths that are created contain a greater number of trees than the number observed during the field study. The number of timber stacks found in each row of timber stacks is then used to determine the number of trees in both the five and four tree wide swaths (Table 4).

Harvester tree selection is kept standard throughout the simulations as is the forwarding pattern. However, the forwarding pattern (the order in which stacks are selected) in the scenarios where larger volumes per stack are presented was altered slightly. The assumption was made that fewer larger stacks would be required to fill the forwarder’s bunk; however, the forwarder would have to travel more often to the depot and back.

Rating of operators was not performed in this study. Due to full shift length observations being conducted, it was assumed that the Hawthorne effect was not applicable to the study. The Hawthorne effect can be defined as a phenomenon where an operator will increase/decrease their rate of work while under observation (Hogg, 2009).

Simulation model construction

Once all time study data is prepared for use as input data into the simulation, the simulation models are created. The steps followed when creating the models are the following:

- Level of detail required for the simulations is established. The outcomes and expectations for each machine are noted and recorded. The main objective is to keep the models simple yet effective enough to generate useful and somewhat detailed outputs.
- The process of each machine is written down on paper and each machine's operation is plotted in a flow chart. The machine processes are simplified versions of the final simulation model. Often the simulated models differ from the draft versions (Hogg, 2009).
- A preliminary simulation model for each machine is created and debugged until it can perform the basic task of assigning each work element a time. The preliminary models were only created to run down one swath of trees for example and were not designed to harvest and extract the entire stand. Only the methods for harvesting and extracting the wood are designed during this step.
- Once the simplified version of each machine is working, machine model complexity is increased making the results of each simulated run more detailed. The models are expanded to run for multiple swaths. The machines now carry out operations over repeated runs of the simulations. An example of the detailed output that could be produced is the measurement of the linear boom distance and angle to each tree per harvester setting.
- Lastly the complex models are verified and validated. This is the final step in the process before the models can be used to generate results that are used for statistical analysis.

Simulation model logic and flow

The simulation is constructed in two parts. The first part covers the operation of the harvester and the second part addresses the operation of the forwarder. The entities in the harvester simulation are individual trees, while for the forwarder they are individual stacks of timber. Unlike conventional simulations created with dedicated simulation software packages, the entities do not compete for a resource (the harvester). Instead the resource is programmed to select entities in a specified order.

Harvester simulation model construction:

As described previously, virtual swaths are created in QGIS. These virtual swaths are then imported into R. Virtual harvester positions are added to the shape file by adding features representing the harvester along the third tree row, at a fixed distance of 4 m between settings. The harvester's position is at a minimum working distance of 0.5 m from the third tree in each setting, this distance is assumed to be from the front of the machine's tracks to the tree.

In the simulation models, only one five row wide swath is used as well as one four row wide swath. As the harvester simulation is run, the swath is replicated at the beginning of each run of the simulation. However, the number of trees per swath varies. This is done by specifying the number of entities at the beginning of each run. Mortality was taken into account in order to keep the simulation as close to the observed system as possible.

The simulation model for the harvester is also divided in two. The first part of the model deals with the harvester working on a five tree wide swath, while the second part deals with the four tree wide swath. Using the Spatstat package (Baddeley & Turner, 2005) as well as the "Maptools" package (Bivand & Lewin-Koh, 2014) in R the lateral boom distance is measured from each harvester position to each one of the 10 trees located per setting. An angle is then calculated from each harvester position to each of the 10 trees per setting. The angle is calculated using simple trigonometry, with the inputs being the lateral boom distance and the spacing between rows (Figure 13 and Figure 14). The tree directly in front of the harvester is considered to be at 90° to the harvester, creating a 180° arc in front of the machine. The angle assigned to each tree is the angle from the row the harvester is straddling to the respective tree.

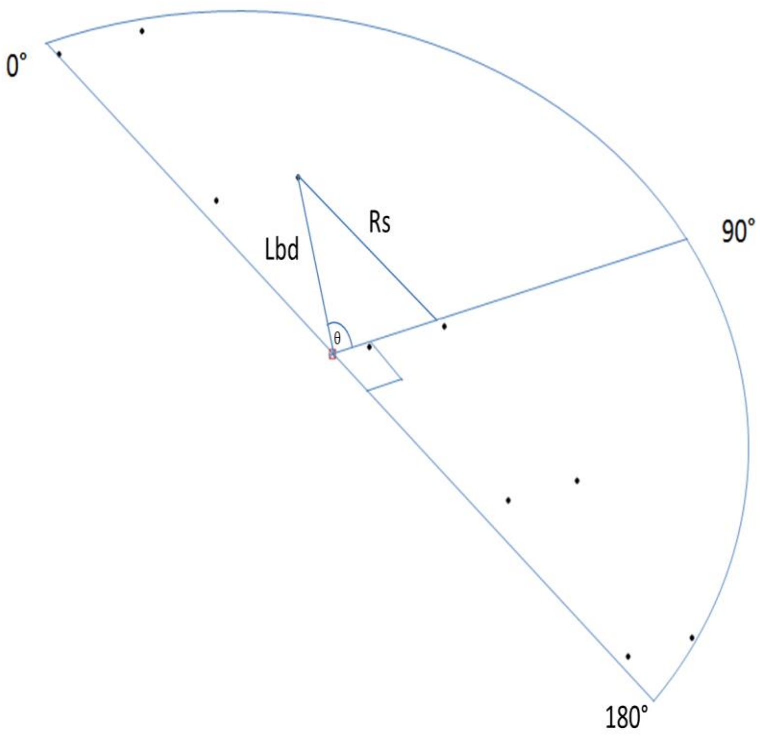

Figure 13: Lateral boom distance (Lbd) and angle to tree (θ) calculation using row spacing (Rs) for a 5 tree wide swath.

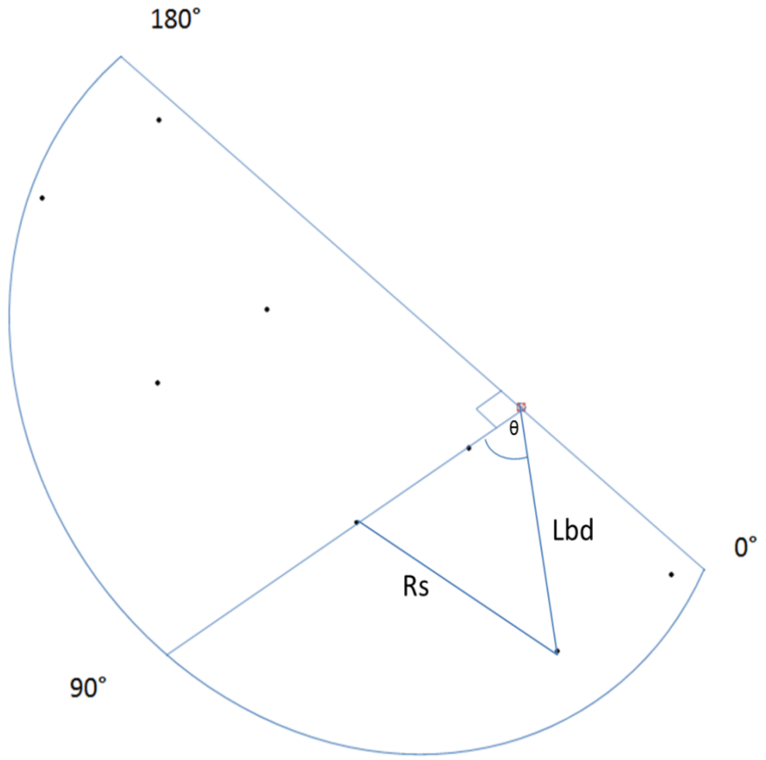

Figure 14: Lateral boom distance (Lbd) and angle to tree (θ) calculation using row spacing (Rs) for 4 tree wide swath.

The resulting output from the above calculations is placed into a data frame containing a row number ranging from 1 to 5 and a tree number. The process for calculating the boom distances and angles for the four-tree-wide swath are performed in the same way as the five-tree-wide swath, with the exception that the harvester now only has eight trees within its reach. The resulting output is placed in the same format as that of the five-row-swath but the row number that is assigned now ranges from 1 to 4.

The number of trees to be felled and processed is created by taking the number of stacks counted per row during the time study and multiplying the number of stacks counted by either 10, for the five tree swath or 8 for the four tree swath. For example each stack received 18 trees due to the process of double stacking (Table 4). This is done as the operator studied has a very irregular felling pattern. Using this method simplified the process while taking the maximum reach of the boom into account.

Table 4: Variables created representing number of trees per swath.

Variable	Number of stacks	Trees per position	Trees per swath
Swath 1	26	10	260
Swath 2	26	8	208
Swath 3	17	10	170
Swath 4	17	8	136
Swath 5	24	10	240
Swath 6	24	8	192
Swath 7	22	10	220
Swath 8	22	8	176

Each of the variables listed in Table 4 are used to create two lists of values from 1 to Swath 8, Swath (i) being the total number of trees in that specific swath. The first list named “swath size 5” containing all the five-row-wide swaths while the second named “swath size 4” contains the four-row-wide swaths. Swath size 5 and Swath size 4 are used as part of a for-loop when running the 5 and 4 row wide swath. The loops run through the two lists applying all functions contained within the loop to each one of swath size variables, effectively applying specified functions to each swath of trees independently.

Values calculated previously relating to boom distances and angles are then joined to the newly created data frame. Values are appended based on tree number so as to match the correct tree with the correct distance and angle. Tree volumes are randomly generated through use of a theoretical probability distribution that matched the actual data recorded during the time study. The values that are generated are controlled through setting the seed (a random number stream) to a value that increases by one every time the "for-loop" was run. This ensures that different volumes are generated each time the simulation is run.

A movement distance of 4 m is added to the output. This is to represent the machine moving two rows forward after completing the felling and processing of the 10 or 8 trees per position.

Each work element for the harvester now has a work element time assigned to it. This is again done through use of theoretical probability distributions. A random number stream control parameter (seed) is used to ensure unique output. The felling processing in the five tree swath would occur in the following sequence (Figure 9): trees 2 - 4 are felled and processed first followed by the remaining trees. Whereas the sequence in the four tree swath was: trees 1 - 3 are felled and processed first followed by the remaining trees.

Delay times (<15 min) could now be modelled. In order to assign a specified amount of delays at random the percentage of delays observed in the real system was first calculated, dividing this value by 100 in order to obtain a numerical value. A uniform distribution is then used to generate a list of values between 0 and 1. A starting value of 0 is chosen and an end value equal to the starting value plus the percentage delays divided by 100. Values that fall between the starting and ending values are identified and assigned a value of 1, while the values outside of the interval are assigned a 0. Using another theoretical probability distribution representing delay time, random work element times are generated and used to overwrite the 1's used as identifier variables. This results in the virtual scenario containing the same percentage of delays as is found in the observed system. This process is summarised in Figure 15.

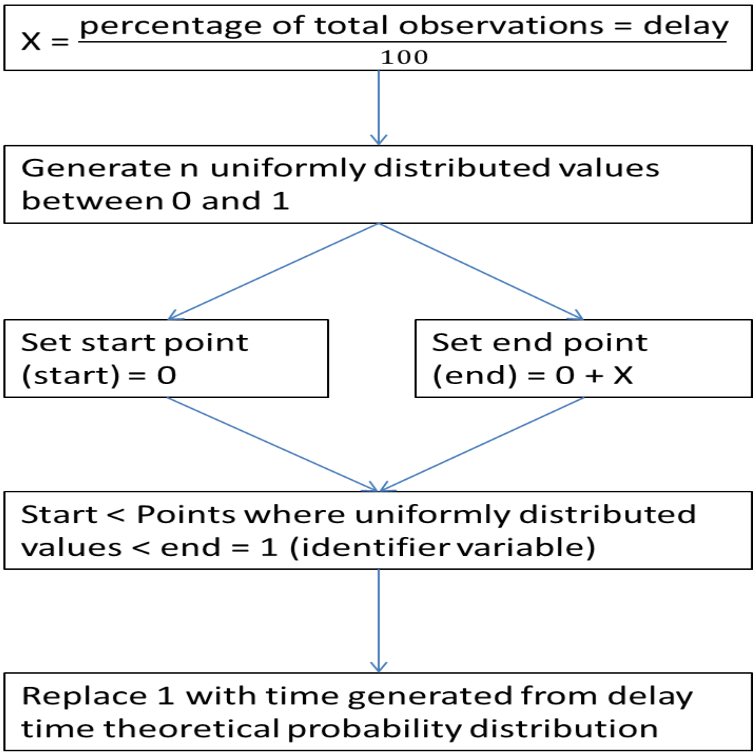

Figure 15: Process of delay modelling.

Work element times are then summed and listed in a total time column within the data frame. The same processes are applied to the second part of the harvester's simulation model representing the four-tree-wide swaths.

The two parts of the harvester simulation, namely the "for-loop" that contain the five-tree-wide swaths and the second for loop that contains the four-tree-wide swaths, are placed inside a for-loop. The for-loop containing the two parts is responsible for running the swath specific loops a specified number of times, in other words, replicating the harvesting of the study area a number of times.

<u>Forwarder simulation model construction:</u>

The stacks created by the harvester are plotted in QGIS. This shape file is imported into R and its metadata data frame contains at this stage stack numbers and the coordinates of each stack. This data frame is to be expanded by appending all outputs from the simulation to it.

Using the same function ("spDistsN1") (Baddeley & Turner, 2005) that is used to measure the distance to trees from the harvester, the distance between each timber stack is measured. These distances are assigned to the corresponding stack numbers in the data frame. Stack volumes can now be calculated. Stack volumes are calculated by generating random values based on the theoretical probability distribution chosen to represent the observed stack volume data. However, this can lead to values being generated for the 89 stacks, that when summed up may have a greater volume than that of the trees that were harvested due to the random assignment of volumes from the probability distribution. To overcome this, a control function in the form of an “If” statement is used. The “If” statement works by summing up the randomly generated stack volumes and comparing the total volume to that of the total harvested volume generated for the five tree and four tree wide swaths. If the summed stack volume (Sv) is subtracted from the summed harvested volume (Hv) the result must lie between 0 and -1. This ensures that slightly less timber is extracted than the volume harvested (This to simulate fibre losses that would occur in reality). The volume generator as well as the “If” statement are placed inside a for-loop in order to generate a list of volumes that meet the requirements of the “If” statement within 1500 repetitions. If no solution can be found an error message is generated. This process is summarised in Figure 16.

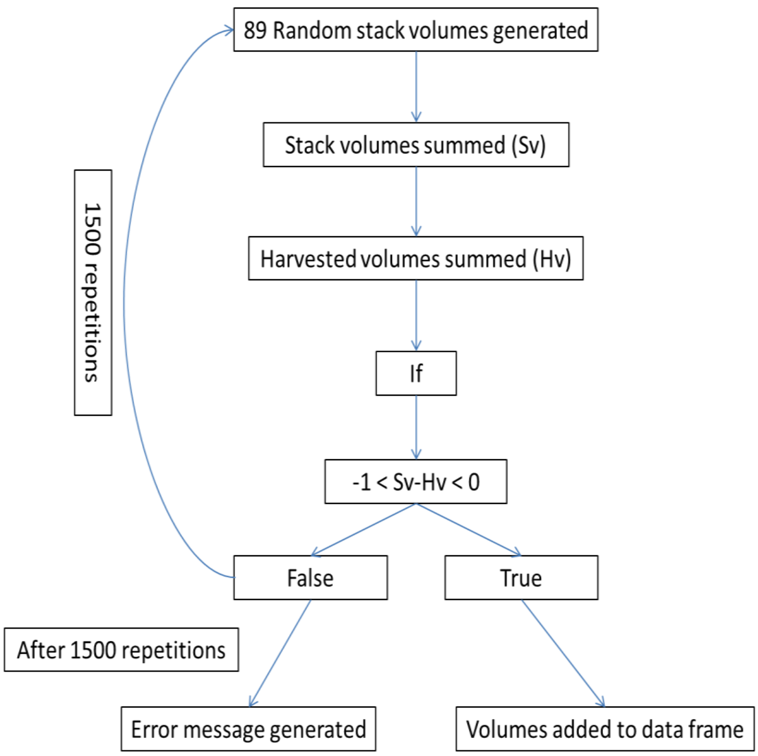

Figure 16: Process of generating stack volumes.

The stacks data frame now includes the stack number, the volume of the stack, the number of the next sequential stack and the distance to the next sequential stack.

Observed forwarder travel is modelled by specifying that the forwarder travel along the road on the south-western border of the compartment to point A (Figure 17) and forwarding timber towards the road at point B. The timber was then forwarded along the road on the north-eastern border of the compartment, from point B to the depot area (Figure 17).

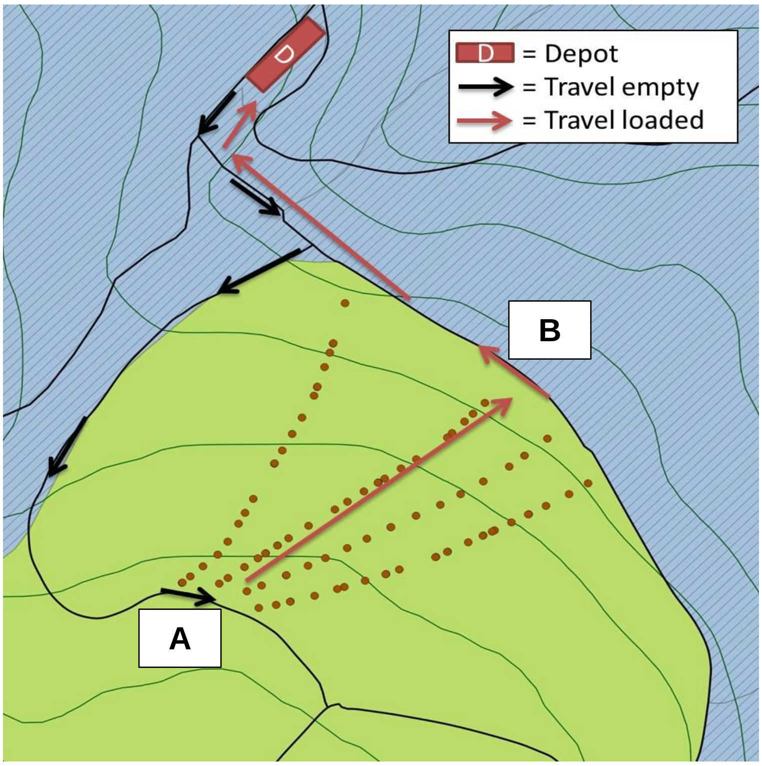

Figure 17: Defined forwarder travel direction.

Average speeds are determined for each element of forwarder travel (Table 22) and are used to create linear models which can then be used to predict travel speeds (Table 11) and subsequently travel times. These linear models are used in combination with a theoretical probability distribution (travel between stack work element). Distances are measured from the depot area to the south-western (point A) and to the north-eastern (point B) side of each row of stacks in the compartment. Using the sequence of stack loading and distances between stacks observed during the time study, cumulative distances can be calculated for in-field travel. The distance to the first stack that is to be loaded per cycle is calculated by summing the distance from the respective road edge that the forwarder enters the compartment from to the first stack that will be loaded. This distance is then used as an input value to the travel off-road empty linear models.

The first speed predicted is travel on-road empty, followed by travel off-road work elements and finally the on-road loaded work element. Once these speeds are added to the data frame they are converted to time (min) (Equation 1):

$$\frac{\left(\frac{Travelled\ Distance\ (m)}{Predicted\ Speed\ (m.s^{-1})}\right)}{60} \qquad (1)$$

The loading work element is calculated using the mean volume of timber per grapple load. Using this mean value (Table 12) enables the calculation of the number of grapple loads it takes to load a stack. This is done by dividing the virtual stack volume by the mean volume of timber per grapple (Equation 2). Multiplying this value with a time per grapple value generated using a theoretical probability distribution yields the time required to load a stack.

$$\frac{Virtual\ Stack\ Volume\ (m^3)}{\left(\frac{Grapple\ Area\ (m^2)}{Mean\ Volume\ Per\ Grapple\ Loading/Unloading\ (m^3)}\right)} \qquad (2)$$

Once a stack is loaded the travel between stacks work element is assigned a randomly generated time, after which the next loading time is calculated. This process is repeated until the forwarder reaches the specified stack at which it is fully loaded and then travels out of the stand. The cumulative distance measured from point B’s road edge to the last stack which the forwarder loaded, is used as the input distance for the travel off-road loaded linear model. Once on the road the distance from the applicable row of stacks to the depot is used as the input distance to the travel on-road loaded linear model. The unloading work element is calculated the same way as the loading time, however, the mean volume per grapple for unloading is used.

Delays for the forwarder are calculated in the same way as that of the harvester. This process is repeated until all 89 timber stacks have been forwarded to the depot area. The entire forwarder work process is placed within a for-loop and set to run for the same number of replications as the harvester.

Model Issues:

Although delays < 15 min are included in the simulation models and their position randomized, it is still possible that the outputs from the models will not match the observed system's data with regards to duration of these delays. Also, the type of delay is not specified in the model. As previously mentioned the machines are simulated on the time frame it takes to finish felling, processing and extracting the timber from the study site. This assumes the machines worked constantly until this objective is achieved. Regular working hours were not taken into account.

Model verification and validation

Verification involves the removal of all anomalies and incoherent logic from the models (Hogg, 2009). A recommended approach to verify a model is through visualisation of the processes; in this way it is possible to see any anomalies occurring which can then be solved. However, in this study no visualisations are used therefore verification of the model had to be performed manually.

As mentioned in Section 2 a process known as tracing (Asikainen, 1995) can be used to intensively study a model and identify issues within the model; this is the method used to verify each machine model in this study. Each process within the model is run individually in a step by step fashion and the output from that process displayed for immediate viewing in order to check for anomalies. Plots of mean times are also generated using the "ggplot2" package (Wickham, 2009). The process of tracing each model is presented in Figure 18 and Figure 19.

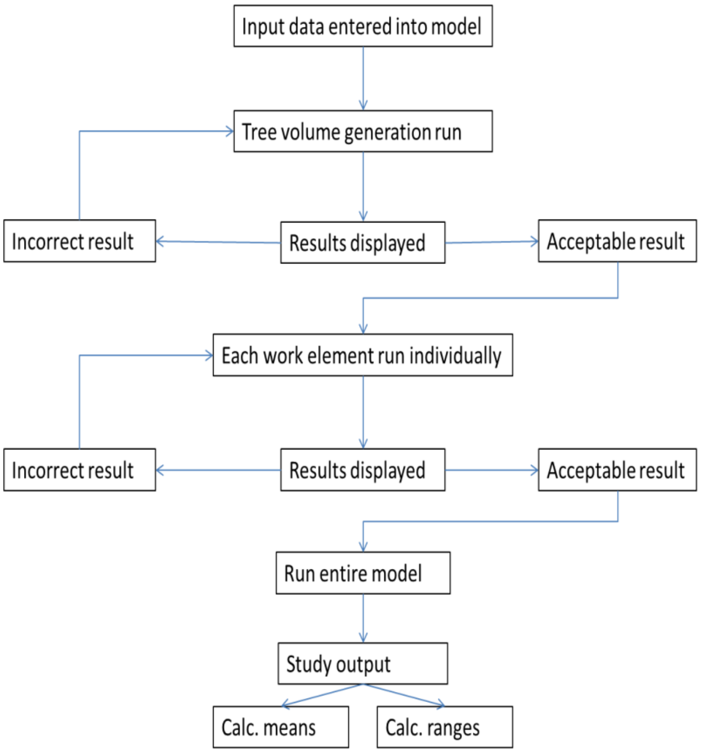

Figure 18: Harvester verification process.

Each process in the model is run individually. Where there are problems with the simulation, corrections are made and the step is run again until the simulation produces the required output. At the end, the entire model is run and each result (work element times and generated volumes) is again checked by calculating the means and ranges for each in order to make sure the model had not generated invalid results. It should be noted that Figure 18 does not include every step of tracing, but only the most important steps.

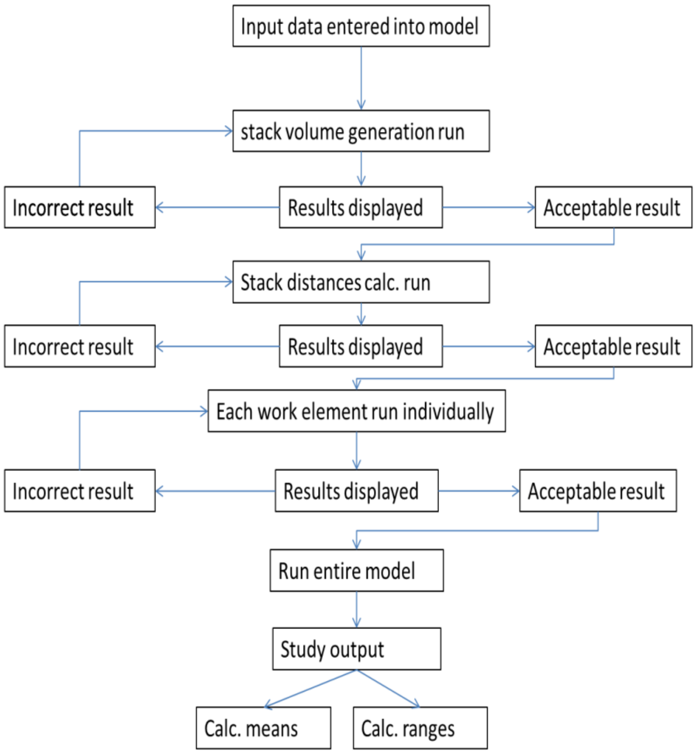

Figure 19: Forwarder verification process.

Verification of the forwarder is slightly more complex than that of the harvester. The reason being that work element times have to correspond to a specific stack number or distance. Each forwarder cycle has to be checked in order to make sure that all work element times were generated and placed in the correct position within the data frame. Again it should be stated that the flow diagram does not include every step of model verification that was performed.

Due to the apparent lack of detailed time study data relating to South African forest harvesting operations, model validation had to be carried out against the data collected during the time study. This is not recommended, as is stated in Reynolds *et al.* (1981). The authors stated that proper validation of stochastic simulation models should be carried out by comparing results against real world data that are independent of the data used in the construction of the model. Even though the model validation method used in this study is not favourable, it can still be done as the model is not to be extrapolated to other sites, etc., therefore the input data was suitable to compare against.

During model validation in simulation projects it often occurs that the outputs generated contain far more observations than that of the real world data it is to be compared against. Along with this, the inability to find the correct theoretical probability distribution of the real world data complicates the process of model validation further. In order to overcome these problems, the real world data is left as is, while a second set of modelled data is generated having the same number of observations as the real world data. Chi-squared tests are used in order to determine whether the modelled values differ significantly from that of the real world data. The null-hypothesis being, that the simulated values do not differ to those in the real world data.

A last point of validation is to ensure that the random number streams created in every theoretical probability distribution, are in fact randomised and do not generate biased results. Validation of this is simple. Every random number stream is controlled through a seed setting function where the value of the seed is set to increase by 1 for every repetition during the simulation. Doing this ensures that each repetition generates a different stream of random values within each theoretical probability distribution. R differs from dedicated simulation software packages in the sense that this step must be performed manually whereas dedicated simulation software has built in random number generators that ensure randomisation automatically.

Alternative scenario modelling

Five separate scenarios are studied, with scenario 1 being the observed system. The modelling of scenarios 2 – 5 is performed by making modifications to the original scenario. These modifications are performed in the following manner.

Scenario 2: In scenario 2 the focus is on the harvester. The forwarder is not taken into account for this simulation as the stack creation and size will be different. Single stacking would be needed to replace the double stacking procedure. Single stacking, as opposed to double stacking, entails the harvester creating a new individual pile of logs after crosscutting at each setting. There is no forwarder data available for single stacking operations.

The same harvester code used to create the original system is retained. However, changes are made at the stage where trees per swath are being calculated. Instead of each stack receiving 10 trees from one swath (cutting in to the compartment) and 8 trees from the returning swath (cutting out of the compartment) (Table 4), each stack now receives 20 trees (Table 5). This represents the harvester felling only five-tree-wide swaths. The same principle is followed when modifying the harvester to only fell four tree wide swaths, however in this case each stack only receives 16 trees.

Table 5: Variables created representing number of trees per swath when felling five tree wide swaths.

Variable	Number of stacks	Trees per position	Trees per swath
Swath 1 (Cut in)	26	10	260
Swath 2 (Cut out)	26	10	260
Swath 3 (Cut in)	17	10	170
Swath 4 (Cut out)	17	10	170
Swath 5 (Cut in)	24	10	240
Swath 6 (Cut out)	24	10	240
Swath 7 (Cut in)	22	10	220
Swath 8 (Cut out)	22	10	220

Table 6: Variables created representing number of trees per swath when felling four tree wide swaths.

Variable	Number of stacks	Trees per position	Trees per swath
Swath 1 (Cut in)	26	8	208
Swath 2 (Cut out)	26	8	208
Swath 3 (Cut in)	17	8	136
Swath 4 (Cut out)	17	8	136
Swath 5 (Cut in)	24	8	192
Swath 6 (Cut out)	24	8	192
Swath 7 (Cut in)	22	8	176
Swath 8 (Cut out)	22	8	176

The new total trees per swath are then linked to the virtual swaths that have been created. The final modification that is required is to ensure that the harvester only moves after felling ten trees. This had to be changed in the second part of the harvester's code (the part that originally dealt with the four row swath in the original scenario). Apart from this there are no other modifications necessary in order to simulate the harvester working only with a larger or smaller swath.

The biggest difference between the original system and scenario 2 is that when the harvester felled and processed the swath in the returning direction (originally the four tree wide swath) the boom is not able to reach the stacks created when felling the adjacent swath. Due to this, single stacking would have to be used. The use of single stacking is an assumed work process as there was no work element in the time study that could measure the boom swinging out to the crosscutting area, as this generally happened simultaneously with the processing work element. Theoretically the boom would still be moving the same distance and direction but the stack would be created 3 m away from the adjacent stack. Model verification and validation is performed in the same way as the original system through the process of tracing.

Scenario 3:   This scenario is based once again on the original system, with a focus on both the harvester and the forwarder. The objective of this scenario is to study the effects of larger tree sizes on the harvester's productivity, while studying the resulting effect of larger stack sizes on forwarder productivity. The harvester simulation is kept the same as scenario 1; however a change is made to the tree volume generator by specifying a higher mean volume. Two larger tree volumes are tested. The original tree volume being 0.14 m^3, followed by 0.2 m^3 and 0.3 m^3. Assuming the harvester still performs double stacking, the resulting log stacks would be substantially larger in volume than in the original system. To account for this, a new average stack volume is calculated by multiplying the number of trees in each stack by the new larger average tree volume. This value is used as the mean value needed when generating random stack volumes. After the forwarding pattern has been modified to account the larger stacks, the simulation model could be run.

Verification and validation of the model is again performed through tracing.

Scenario 4:   The objective of scenario 4 is to model the forwarder's productivity when forwarding the original sized stacks (mean = 2.5 m^3) over increasing road distance. The infield travel distances and forwarding pattern remained the same as that of the original system, however, the road distances (measured to the furthest row of stacks) started at a value of 0 m. This represented forwarding only to roadside, the increments increased by 200 m intervals until reaching a maximum distance of 1000 m.

The original forwarder model is again used as the backbone for this scenario and the only modification necessary is to insert the new forwarding distances into the model each time the simulation is run. As shown in previous sections, the travel on/off-road distances were modelled using linear models.

Model verification and validation is carried out using the process of tracing. It should be kept in mind that the linear models used to calculate travel times will produce a somewhat inaccurate representation of reality (Table 11). This is also true as the models had to extrapolate times when modelling distances greater than that of the original system.

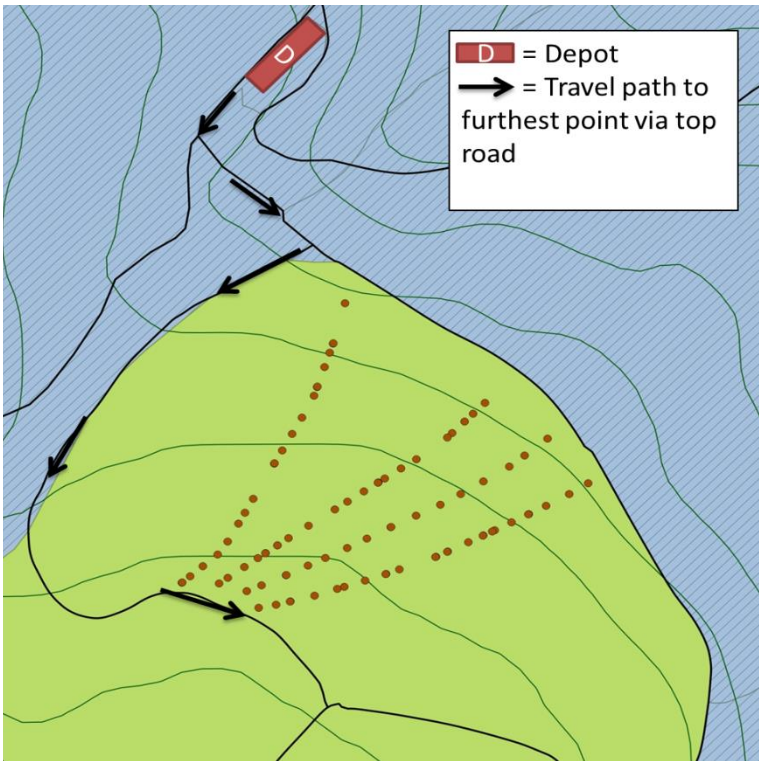

Figure 20: Furthest forwarding distance via south-western road.

Scenario 5: The focus is to model the forwarder across a range of distances in a similar fashion to that of scenario 4. The difference between scenario 4 and scenario 5 is that scenario 5 only used one road (the road running along the north-eastern boundary of the study site) to forward timber to the depot. The original forwarder model is used as the backbone. It is modified by removing all the code that relates to the forwarder travelling along the road on the south-western side of the compartment. The forwarder is programmed to travel from the depot area along the road running along the north-eastern compartment boundary to a row of stacks, at which point it enters the compartment and a cumulative sum of the in-field travel distance begins. The forwarder travels to the furthest stack and begins loading. The forwarder then moves back down the path it travelled towards the north-eastern boundary road. Once fully loaded the distance remaining from the road edge to the forwarders position is used as the input to the linear model responsible for calculating travel off-road loaded. The forwarder then returns to roadside and travels back along the north-eastern road to the depot area.

Due the roads being different lengths the distance from the depot to the south-western side of the furthest row of stacks, was an average of 100 m greater than the distance from the depot to the north-eastern side of the row of stacks. For this scenario the maximum road travel distance was set at 900 m as opposed to the 1000 m used in scenario 4. The on road travel distances increased in 200 m intervals.

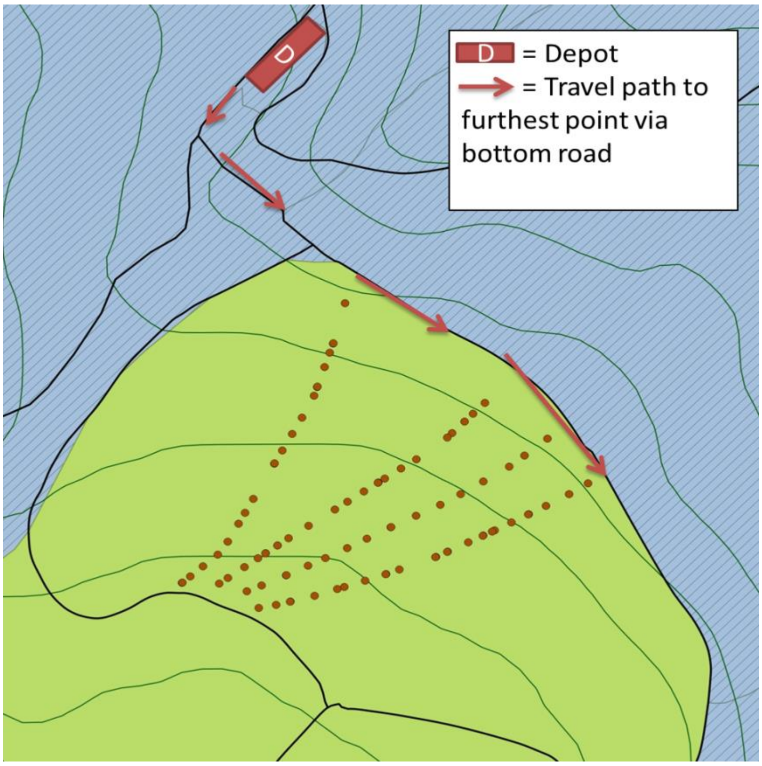

Figure 21: Furthest forwarding distance via north-eastern road.

Verification and validation is performed through tracing each model and carefully inspecting the output for anomalies.

Model cost calculations

Machine costing is performed using a costing model developed by Ackerman *et al.* (2014). It uses standard cost calculation functions to determine both the cost per productive machine hour (R PMH^{-1}) as well as cost per cubic metre (R m^{-3}) for individual machines.

Costs were calculated by inserting all required fixed and variable costs into the costing model as well as the machine utilization and average productivity calculated per harvesting scenario for both the harvester and the forwarder.

Costs calculated did not however include overhead costs, support equipment or personnel costs, risk compensation or profit margin.

Assumptions of the machine costing were the following:

- Both machines were scheduled to work 6 days per week totalling 312 days per year.
- Two shifts were worked per day.
- Each shift was 9 hours in length (SMH).
- Expected economic life of both the harvester and forwarder was set at 20 000 hours.
- Machine utilisation was kept constant for each scenario.

The reason the machine utilisation is kept constant between scenarios is due to the machines being modelled off the current system's data specifically including delay data. Each repetition of each scenario has the same amount of non-productive time as the observed system. Using the theoretical probability distributions also generates times similar to those of the observed system. Another factor that led to this decision is the fact that the operation is not split into shifts as mentioned in previous sections. If the object of the study was to study the system as a whole this approach would be unsuitable. Machine utilisation for the harvester is set at 67% while machine utilisation for the forwarder is set at 87%. Machine utilisation is calculated using Equation 3 (Hogg *et al.*, 2012):

$$Utilisation(\%) = \left(\frac{PMH}{SMH}\right) \times 100 \qquad (3)$$

Where:

PMH = Productive Machine Hours (h).

SMH = Scheduled Machine Hours (h).

Mean productivity in m^3 h^{-1} for each scenario is calculated using Equation 4:

$$\frac{\sum_{n=1}^{n}\left(\frac{Vol.}{\frac{WET}{60}}\right)}{n} \qquad (4)$$

Where:

Vol. = Tree volume or cumulative volume of stacks at time of unloading. (m^3)

WET = Work Element Time. (min)

Statistical Analysis

Statistical analysis is carried out using Statistica 10 software package (Statsoft 2012). Each scenario is tested using repeated measures analysis of variance (ANOVA) for differences between the productivities of the original machine work method and the alternative working method. The null hypothesis is that the two productivities did not differ from each other. Due to the data not being normally distributed, a method called “bootstrapping” is used. Bootstrap means are used for graphical representation of significant results.

4. Results

Machine observation

The harvester and forwarder were observed for a combined total of 31 h (1858.3 min) during the time study (Table 7).

Table 7: Cumulative observed time per machine.

Machine	Observed time (cmin)	Observed time (h)
Harvester	1287.0	21.5
Forwarder	571.3	9.5

Machine work element time distributions and linear models

Due to R not containing a few of the distributions that were described as the best fitting according to the Input Analyser software (for example the Erlang distribution), the theoretical probability distributions fitted in R differed in some instances to the input data. Differences between recorded data and the fitted probability distributions values are seen when the two are tested against each other using a Kolmogorov-Smirnov test (Table 8 and Table 9). P-values less than 0.05 indicate that there is a significant difference between the actual data's distribution and the distribution chosen that best fits the data, thus rejecting the null hypothesis that the two distributions do not differ.

Table 8: Harvester work element time theoretical probability distributions.

Variable	Unit	Fitted Distribution	Parameters	P-value
Tree volumes	m^3	Weibull	shape = 1.7; scale= 0.19	<0.05
Boom out	cmin	Lognormal	meanlog= -2.62; Sdlog= 0.47	<0.05
Boom in	cmin	Lognormal	meanlog= -3.32; sdlog= 0.57	<0.05

Variable	Unit	Fitted Distribution	Parameters	P-value
Fell	cmin	Lognormal	meanlog= -2.91; sdlog= 0.67	<0.05
Process	cmin	Weibull	shape= 2.41; scale = 0.56	<0.05
Move	cmin	Lognormal	meanlog= -2.35; sdlog= 0.71	0.9
Delays	cmin	Gamma	shape= 0.52, rate = 0.62	<0.05

Table 9: Forwarder work element time theoretical probability distributions.

Variable	Unit	Fitted Distribution	Parameters	P-value
Stack volumes	m^3	Weibull	shape= 3.40; scale= 2.81	0.98
Travel between stack	cmin	Lognormal	meanlog= -1.37; sdlog=0.80	0.11
Time per grab (loading)	cmin	Lognormal	meanlog= -0.24; sdlog=0.57	<0.05
Time per grab (unloading)	cmin	Uniform	min=0.20; max=0.60	<0.05
Delays	cmin	Weibull	shape= 1.68; scale= 0.68	<0.05

Forwarder travel elements that are not included in the above table are: travel on-road empty/loaded and travel off-road empty/loaded. These work element times are modelled using linear regression, where speed is determined as a function of respective travel distance (Table 10). A reason for using speed as a function of distance measured in metres (Dist.) is that it yielded a model with a much higher R^2 than a model created using travel time as a function of distance. Work element times for these forwarder travel elements are then calculated from the predicted speeds at a later stage.

Table 10: Forwarder travel linear model parameters, standard errors and R^2 values.

Work element	Parameters of LM	Standard Error	R^2 of model
Travel on-road empty	Intercept = 0.17 Dist. (m) = 0.01	Intercept = 0.67 Dist. (m) = 0.001	0.44
Travel off-road empty	Intercept = 0.01 Dist. (m) = 0.01	Intercept = 0.25 Dist. (m) = 0.01	0.46
Travel off-road loaded	Intercept = 0.30 Dist. (m) = 0.004	Intercept = 0.09 Dist. (m) = 0.001	0.67
Travel on-road loaded	Intercept = 2.66 Dist. (m) = 0.002	Intercept = 0.49 Dist. (m) = 0.001	0.38

The four forwarder travel elements linear models can be found in Table 11.

Table 11: Linear models of forwarder travel elements.

Work element	Linear model
Travel on-road empty	Speed(m s^{-1}) = 0.01(dist.) + 0.25
Travel off-road empty	Speed(m s^{-1}) = 0.01(dist.) + 0.01
Travel off-road loaded	Speed(m s^{-1}) = 0.004(dist.) + 0.30
Travel on-road loaded	Speed(m s^{-1}) = 0.002(dist.) + 2.66

Forwarder loading and unloading

A ratio is determined for the amount of timber loaded and unloaded per grapple. This is done by determining the average amount of timber that was in each grapple load during the time study period. The resulting mean values are the volume of timber per grapple load for loading (0.86 m^3) and unloading (0.98 m^3). The mean volume per grapple load is higher for the unloading element. Work element times for the loading and unloading are calculated by dividing the volume per stack that is to be loaded by the respective mean volume per grapple load value. This determines the number of grabs required to load a stack or unload the forwarder. Using the theoretical probability distribution listed in Table 9 a work element time is generated for each grapple load required to load/unload the forwarder. This randomly generated time is multiplied by the number of grapples required to load a stack or unload the forwarder thus determining the loading and unloading work element times.

Table 12: Mean volume per grapple load ratio calculation for loading and unloading.

Work element	Original grapple (0.8 m^2)	Larger grapple (1 m^2)
Load	$\frac{0.8}{0.86}$	$\frac{1}{0.86}$
Unload	$\frac{0.8}{0.98}$	$\frac{1}{0.98}$

When calculating the new mean stack sizes that occur due to the harvester felling and processing larger trees, three new average stack volumes are found (Table 13).

Table 13: Average stack volumes.

Average tree volume (m^3)	Number of trees per stack	Average stack volume (m^3)
0.14	18	2.5
0.2	18	3.6
0.3	18	5.4

Along with the modification to the stack volume generator (modified to generate larger mean stack volumes) of the forwarders simulation model, the forwarding pattern has to change as well. The original pattern is assumed to be no longer suitable as the forwarder will be grossly overloaded if the same number of stacks are loaded per cycle. To counter this problem the average load volume is calculated for each cycle observed during the time study. When forwarding the 3.6 m^3 stacks the average number of stacks that are loaded before heading to the depot was four stacks, whereas when forwarding 5.4 m^3 stacks the average number of stacks loaded decreases to three stacks. As previously mentioned the forwarder was programmed to only load full stacks, due to this when loading 3.6 m^3 stacks the load bunk was slightly underutilised as loading the bunk fully would lead to over loading. When loading the 5.4 m^3 stacks the bunk had to be over loaded otherwise the forwarder's bunk would be severely underutilised. Table 14 lists the average volume per cycle that the forwarder extracts. With the new average forwarder load volumes it is further assumed that with an increase in stack volume the forwarder travels to the depot more frequently as it loads fewer stacks.

The forwarder is also modelled extracting various sized stacks using a larger grapple (1 m^2). To do this, the larger grapple ratio that is calculated (Table 12) is used instead of the standard grapple ratio.

Table 14: Average forwarder load per cycle.

Average stack size (m^3)	Average volume extracted per cycle (m^3)
2.5	15.8
3.6	15.3
5.4	17.4

Machine model validation

Chi-squared tests were used to compare the generated work element times against the real data. The tests indicate that none of the work element distributions generated values that differ significantly from those observed in the real world data (Table 15 and Table 16). This is important to note as it is previously mentioned that R does not contain all the relevant theoretical probability distributions. In most cases the second best fitting distribution has to be used. Results of the Chi-squared test can be found in Table 15 and Table 16.

Table 15: Chi squared test validation of harvester simulation outputs.

Variable	LM / Distribution	p-value	Reject / do not reject H_0
Boom out	Probability Distr.	0.24	Do not reject H_0
Boom in	Probability Distr.	0.24	Do not reject H_0
Fell	Probability Distr.	0.25	Do not reject H_0
Process	Probability Distr.	0.24	Do not reject H_0
Move	Probability Distr.	0.24	Do not reject H_0
Delays	Probability Distr.	0.24	Do not reject H_0

Table 16: Chi squared test validation of forwarder simulation outputs.

Variable	LM / Distribution	p-value	Reject / do not reject H_0
Travel on-road empty	Linear Model	<0.05	Reject H_0
Travel off-road empty	Linear Model	<0.05	Reject H_0
Travel off-road loaded	Linear Model	0.23	Do not reject H_0
Travel on-road loaded	Linear Model	<0.05	Reject H_0
Travel between stack	Probability Distr.	0.24	Do not reject H_0
load	Probability Distr.	0.240	Do not reject H_0
Unload	Probability Distr.	0.23	Do not reject H_0

Variable	LM / Distribution	p-value	Reject / do not reject H_0
Delays	Probability Distr.	0.23	Do not reject H_0

As is seen in Table 16 the work elements travel off-road empty, travel off-road loaded and travel on-road loaded have a p-value less than 0.05, indicating that the generated work element times differ significantly from the real data. This is due to the poor fit of the linear models that are used. These models are however necessary as they are needed to model the forwarder when working with increasing forwarding distance intervals, that increased by 200 m per repetition of the simulation. Table 17 highlights the differences between mean times of the real world data and the simulated output for the travel elements. All forwarder travel time linear models predict lower times than the observed real world times. These models are not ideal but as previously stated they are the only option to model the forwarder travel at increasing distances.

Table 17: Mean differences between real world and predicted data.

Work element	Mean time (cmin) Real world data	Mean time (cmin) Simulated data	Linear model R^2
Travel between stack	0.41	0.32	-
Travel on-road empty	3.32	1.80	0.44
Travel off-road empty	2.02	1.10	0.46
Travel off-road loaded	3.07	2.78	0.67
Travel on-road loaded	2.44	0.41	0.38

The travel between stack work element is not modelled using a linear model but through use of theoretical probability distribution instead, hence the lack of an R^2 value in Table 17.

Equipment results and comments

Table 18 provides a summary of the scenario costs for the harvester as well as the productivity calculated using PMH and utilisation rates. Table 19 provides a summary of the scenario costs for the forwarder, as well as the productivity and utilisation rates.

Table 18: Harvester utilisation, productivity, average cycle time and cost.

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin setting^{-1})	Cost (R m^{-3})
Felling + processing 0.14m^3 trees	67	11.43	6.78	65.89
Felling + processing 0.2m^3 trees	67	16.69	6.95	45.13
Felling + processing 0.3m^3 trees	67	24.57	6.96	30.65
Felling + processing 4 tree wide swath	67	11.30	6.03	66.65
Felling + processing 5 tree wide swath	67	10.77	7.65	69.93

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin setting^{-1})	Cost (R m^{-3})
Felling + processing 4 and 5 tree wide swath	67	11.43	6.78	65.89

Table 19: Forwarder utilisation, productivity, average cycle time and cost.

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin cycle^{-1})	Cost (R m^{-3})
Forwarding 2.5m^3 stacks	87	29.91 29.78*	31.59 31.72*	33.21 33.36*
Forwarding 3.6m^3 stacks	87	29.15 29.12*	32.28 32.31*	34.08 34.12*
Forwarding 5.4m^3 stacks	87	30.92 30.82*	34.75 34.83*	32.13 32.23*
Forwarding 2.5m^3 stacks using larger grapple	87	34.24 34.09*	27.49 27.61*	28.53 29.14*
Forwarding 3.6m^3 stacks using larger grapple	87	33.42 33.39*	27.99 28.02*	29.73 29.75*
Forwarding 5.4m^3 stacks using larger grapple	87	35.82 35.69*	29.88 29.96*	27.73 27.84*

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin $cycle^{-1}$)	Cost (R m^{-3})
Forwarding double road 0m	87	36.58 36.39*	26.20 26.32*	27.16 27.30*
Forwarding double road 200m	87	31.73 32.9*	29.87 29.83*	31.31 30.20*
Forwarding double road 400m	87	30.36 30.34*	31.15 31.16*	32.72 32.74*
Forwarding double road 600m	87	29.52 29.31*	31.99 32.21*	33.65 33.89*
Forwarding double road 800m	87	28.92 28.66*	32.62 32.91*	34.35 34.66*
Forwarding double road 1000m	87	28.46 28.18*	33.12 33.44*	34.91 35.25*
Forwarding double road 0m using larger grapple	87	43.17 42.92*	22.09 22.21*	23.01 23.15*
Forwarding double road 200m using larger grapple	87	36.64 38.21*	25.76 24.73*	27.11 26.00*

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin $cycle^{-1}$)	Cost (R m^{-3})
Forwarding double road 400m using larger grapple	87	34.83 34.82*	27.05 27.05*	28.52 28.53*
Forwarding double road 600m using larger grapple	87	33.74 33.47*	27.88 28.10*	29.94 29.68*
Forwarding double road 800m using larger grapple	87	32.97 32.63*	28.51 28.80*	30.13 30.45*
Forwarding double road 1000m using larger grapple	87	32.38 32.01*	29.02 29.34*	30.68 31.04*
Forwarding single road 0m	87	31.35	30.33	31.69
Forwarding single road 100m	87	29.56	36.61	33.61
Forwarding single road 300m	87	26.83	35.04	37.03
Forwarding single road 500m	87	26.12	35.96	38.03

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin $cycle^{-1}$)	Cost (R m^{-3})
Forwarding single road 700m	87	25.62	36.63	38.78
Forwarding single road 900m	87	25.24	37.16	39.36
Forwarding single road 0m using larger grapple	87	36.46	26.05	27.25
Forwarding single road 100m using larger grapple	87	33.88	29.13	30.76
Forwarding single road 300m using larger grapple	87	32.27	33.41	30.79
Forwarding single road 500m using larger grapple	87	30.05	32.67	33.86
Forwarding single road 700m using larger grapple	87	29.60	32.34	33.56

Scenario	Machine Utilisation (%)	Average Machine productivity (m^3 hr^{-1})	Average cycle time (cmin $cycle^{-1}$)	Cost (R m^{-3})
Forwarding single road 900m using larger grapple	87	28.96	32.87	34.30

*** indicate cycles where the forwarder worked from point B towards point A.**

It is important to note that individual costing of each machine operating in the observed system is only applicable to the site and the conditions in which the machine was observed.

Felling and processing of the varying tree sizes will not yield different cycle times when simulated, as the work element times for the harvester were generated using theoretical probability distributions as previously mentioned. In reality the law of piece size would be applicable, but due to the random time generation used this will not be evident in this study's simulation. Time taken for the harvesting and processing of the larger trees may not differ to those for harvesting and processing of the smaller trees, however, the productivity values for each scenario should differ significantly.

When studying the cost per m^3, some comparisons relating to cost and total time per cycle are to be made between scenarios. These comparisons can be found in Table 20 for the harvester and Table 21 for the forwarder. The differences are calculated by comparing each respective scenario against the original observed system (scenario 1).

Table 20: Changes in average cycle time, productivity and cost when comparing different harvester scenarios.

Scenario	Average cycle time (cmin cycle^{-1})	Average Machine productivity (m^3 hr^{-1})	Cost (R m^{-3})
Original observed system	6.78	11.43	65.89
Felling + processing 0.2m^3 trees	0	+5.26	-20.76
Felling + processing 0.3m^3 trees	0	+13.14	-35.24
Felling + processing 4 tree wide swath	-0.75	-0.13	+0.76
Felling + processing 5 tree wide swath	+0.87	-0.66	+4.04

+ indicate increase from original scenario; - indicate decrease from original scenario

Table 21: Changes in average cycle time, productivity and cost when comparing different forwarder scenarios.

Scenario	Average cycle time (cmin cycle^{-1})	Average Machine productivity (m^3 hr^{-1})	Cost (R m^{-3})
Original observed system	31.59 31.72*	29.91 29.78*	33.21 33.36*
Forwarding 3.6m^3 stacks	+0.69 +0.59*	-0.76 -0.66*	+0.87 +0.76*
Forwarding 5.4m^3 stacks	+3.16 +3.11*	+1.01 +1.04*	-1.08 -1.13*
Forwarding 2.5m^3 stacks using larger grapple	-4.10 -4.11*	+4.33 +4.31*	-4.68 -4.22*
Forwarding 3.6m^3 stacks using larger grapple	-3.60 -3.70*	+3.51 +3.61*	-3.48 -3.61*

Scenario	Average cycle time (cmin cycle^{-1})	Average Machine productivity (m^3 hr^{-1})	Cost (R m^{-3})
Forwarding 5.4m^3 stacks using larger grapple	-1.71 -1.76*	+5.91 +5.91*	-5.48 -5.52*
Forwarding double road 0m	-5.39 -5.40*	+6.67 +6.61*	-6.05 -6.06*
Forwarding double road 200m	-1.72 -1.89*	+1.82 +3.12*	-1.90 -3.60*
Forwarding double road 400m	-0.44 -0.56*	+0.45 +0.56*	-0.49 -0.62*
Forwarding double road 600m	+0.40 +0.49*	-0.39 -0.47*	+0.44 +0.53*
Forwarding double road 800m	+1.03 +1.19*	-0.99 -1.12*	+1.14 +1.30*
Forwarding double road 1000m	+1.53 +1.72*	-1.45 -1.6*	+1.70 +1.89*
Forwarding double road 0m using larger grapple	-9.50 -9.51*	+13.26 +13.14*	-10.20 -10.21*
Forwarding double road 200m using larger grapple	-5.83 -6.99*	+6.73 +8.43*	-6.10 -7.36*
Forwarding double road 400m using larger grapple	-4.54 -4.67*	+4.92 +5.04*	-4.69 -4.83*
Forwarding double road 600m using larger grapple	-3.71 -3.62*	+3.83 +3.69*	-3.27 -3.68*
Forwarding double road 800m using larger grapple	-3.08 -2.92*	+3.06 +2.85*	-3.08 -2.91*

Scenario	Average cycle time (cmin cycle^{-1})	Average Machine productivity (m^3 hr^{-1})	Cost (R m^{-3})
Forwarding double road 1000m using larger grapple	-2.57 -2.38*	+2.47 +2.23*	-2.53 -2.32*
Forwarding single road 0m	-1.39	+1.57	-1.67
Forwarding single road 100m	+4.89	-0.22	+0.25
Forwarding single road 300m	+3.32	-2.95	+3.67
Forwarding single road 500m	+4.24	-3.66	+4.67
Forwarding single road 700m	+4.91	-4.16	+5.42
Forwarding single road 900m	+5.44	-4.54	+6.00
Forwarding single road 0m using larger grapple	-5.67	+6.68	-6.11
Forwarding single road 100m using larger grapple	-2.59	+4.10	-2.60
Forwarding single road 300m using larger grapple	+1.69	+2.49	-2.57
Forwarding single road 500m using larger grapple	+0.95	+0.27	+0.50
Forwarding single road 700m using larger grapple	+0.62	-0.18	+0.20

Scenario	Average cycle time (cmin cycle^{-1})	Average Machine productivity (m^3 hr^{-1})	Cost (R m^{-3})
Forwarding single road 900m using larger grapple	+1.15	-0.82	+0.94

+ indicate increase; - indicate decrease; * indicate cycles where the forwarder worked from point B towards point A.

The comparisons against Scenario 1 cover the differences between the alternative scenarios and the original observed system. These differences are based purely on the outputs derived from either the simulation models or the costing model. The following detailed comparisons (statistically tested) expand on Table 20 and Table 21.

Scenario 2: The simulation outputs, namely the mean productivity values for each method are tested using the Bootstrap method of statistical analysis on a 95% confidence interval. The output from the test can be found in Figure 22. Felling and processing a 4 tree wide swath or a combination of 4 and 5 tree wide swaths did not differ significantly in productivity from each other, whereas felling and processing a 5 tree wide swath differed significantly in productivity from felling both a 4 tree wide swath and a combination.

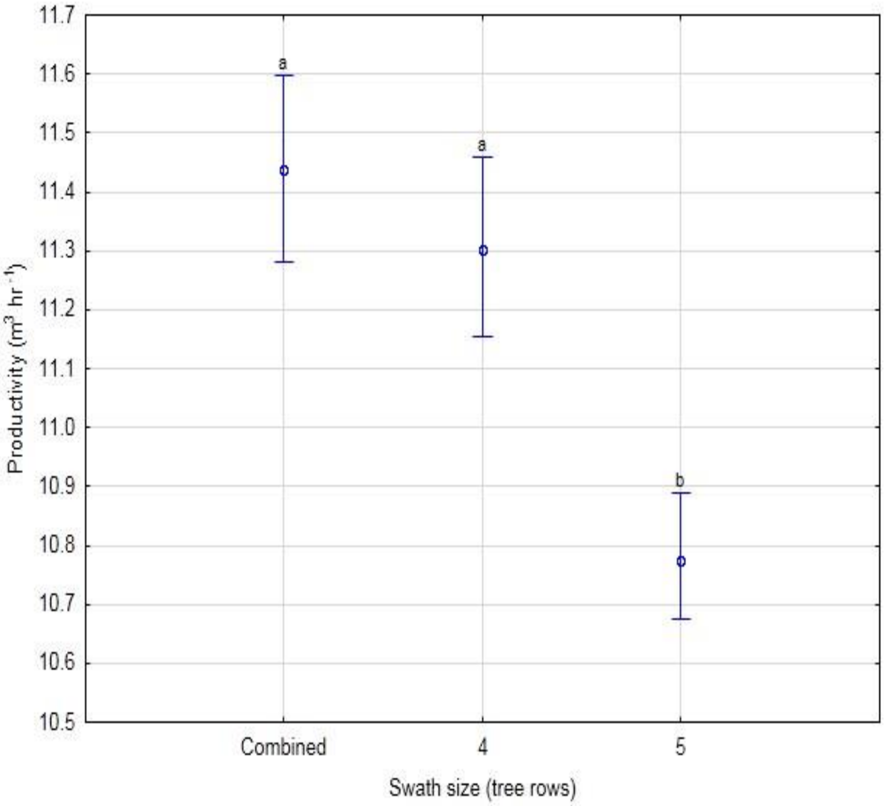

Figure 22: Bootstrap means of harvester productivity when felling different swath sizes on a 95% confidence interval (letters above bars that differ indicate significant difference).

Scenario 3: The harvester's mean productivity values when felling and processing each tree size differed significantly in terms of productivity from each other (Figure 23).

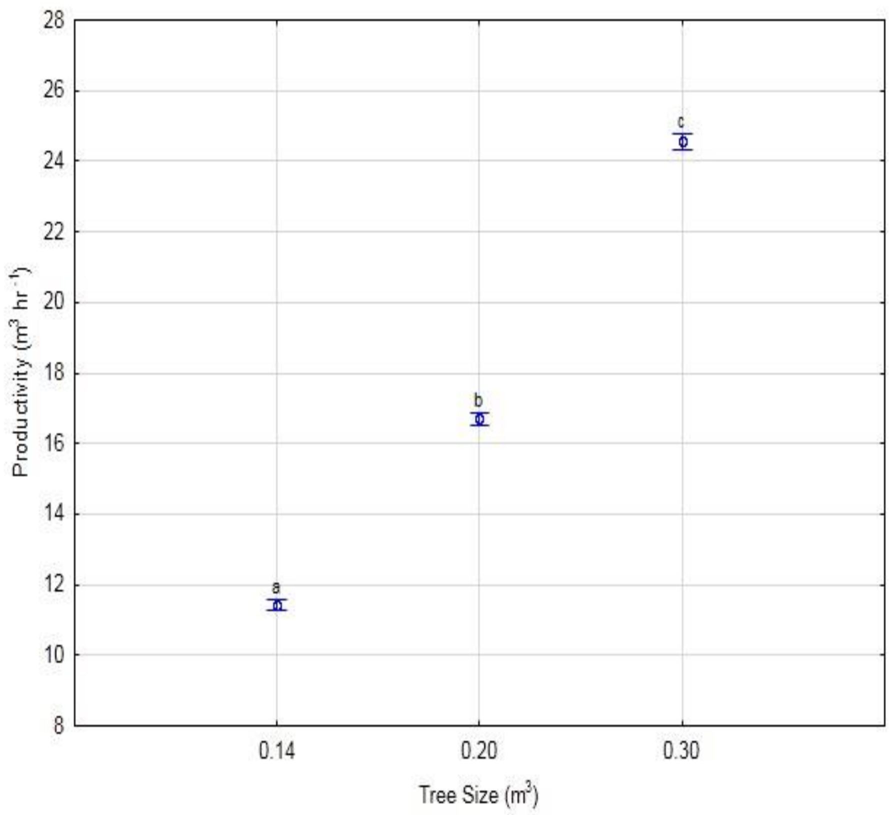

Figure 23: Bootstrap means of harvester productivity when felling different tree sizes on a 95% confidence interval (letters above bars that differ indicate significant difference).

When testing the effects of larger volume stacks on forwarder productivity the following was found. The forwarding direction for each stack size, either A – B (Figure 17) (i.e. entering the compartment using the road on the south-western side and exiting onto the road located on the north-eastern side), or B – A (Figure 17) (i.e. entering the compartment road located on the north-western side of the compartment and exiting onto the road located on the south-western side of the compartment) did not yield any significant differences in productivity (Figure 24).

When simulating using the standard grapple, a significant difference in productivity is noted between forwarding log stacks with an average volume of 3.6 m^3 and 5.4 m^3 both in an A – B direction. However, no significant difference in productivity is noted when forwarding log stacks with an average volume of 3.6 m^3 in an A – B direction and 5.4 m^3 stacks in a B – A direction (Figure 24).

There are significant differences in productivity between forwarding log stacks with an average volume of 3.6 m^3 in a B – A direction, and 5.4 m^3 in both forwarding directions(A – B and B – A) (Figure 24).

When simulating the forwarder using the larger grapple significant differences in productivity were found between extracting log stacks with a mean volume of 3.6 m^3 in both directions (A – B and B – A) and logs stacks with a mean volume of 5.4 m^3 in both directions (A – B and B – A) (Figure 24).

Significant differences in productivity are noted between the forwarding of all stack sizes when comparing the standard grapple against the larger grapple (Figure 24).

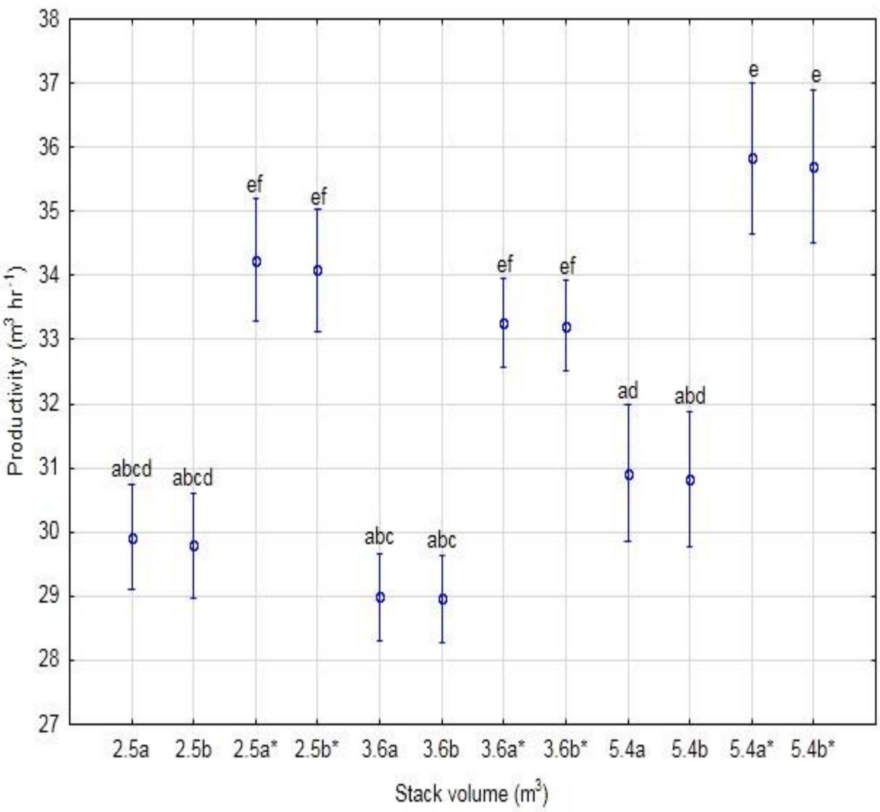

Figure 24: Bootstrap means of forwarder productivity when extracting various stack volumes using both grapple sizes on a 95% confidence interval (letters above bars that differ indicate significant difference, * indicate scenarios where large grapple was used, distances marked with an "a" indicate instances of forwarding in A-B direction, distances marked with a "b" indicate instances of forwarding in B-A direction).

Scenario 4: Simulation output of the forwarder fitted with the standard grapple, extracting log assortments via the two roads indicates significant differences in productivity as a result of forwarding direction at the 200 m, 600 m, 800 m and 1000 m road distance intervals. No significant differences in productivity are found as a result of forwarding direction at the 0 m and 400 m distance intervals (Figure 25).

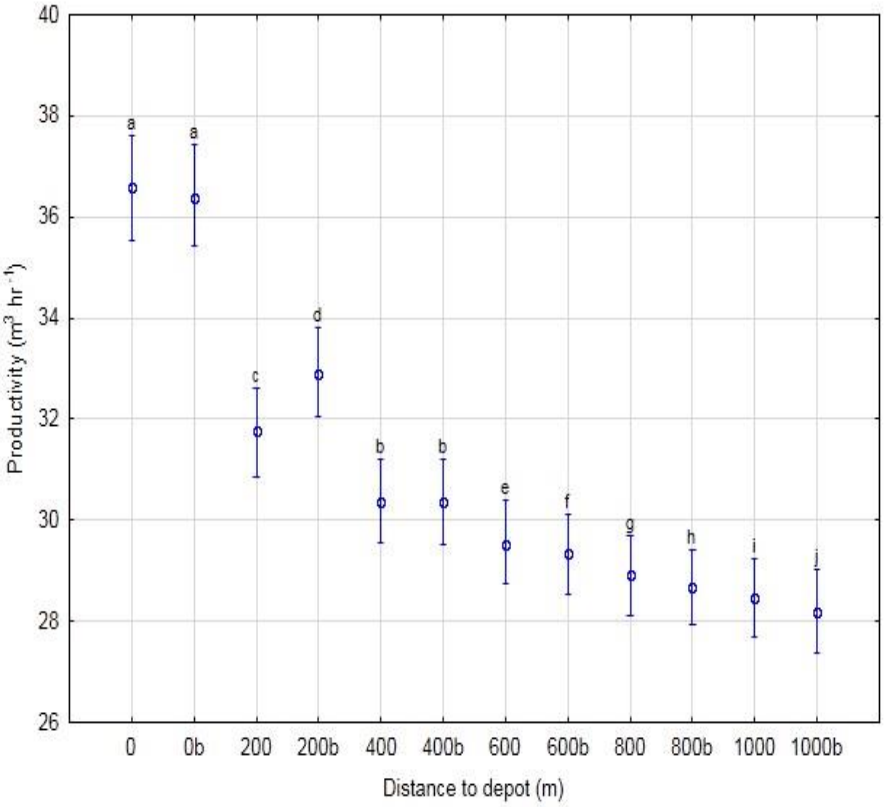

Figure 25: Bootstrap means of forwarder productivity when extracting to increasing depot distances using the standard grapple on a 95% confidence interval (letters above bars that differ indicate significant difference, distances marked with a "b" indicate instances of forwarding in B-A direction).

Simulation output of the forwarder fitted with the larger grapple, extracting log assortments via the two roads indicates significant differences in productivity at the 200 m, 600 m, 800 m and 1000 m on-road distance intervals. No significant differences in productivity are found as a result of forwarding direction at the 0 m and 400 m on-road distance intervals (Figure 26).

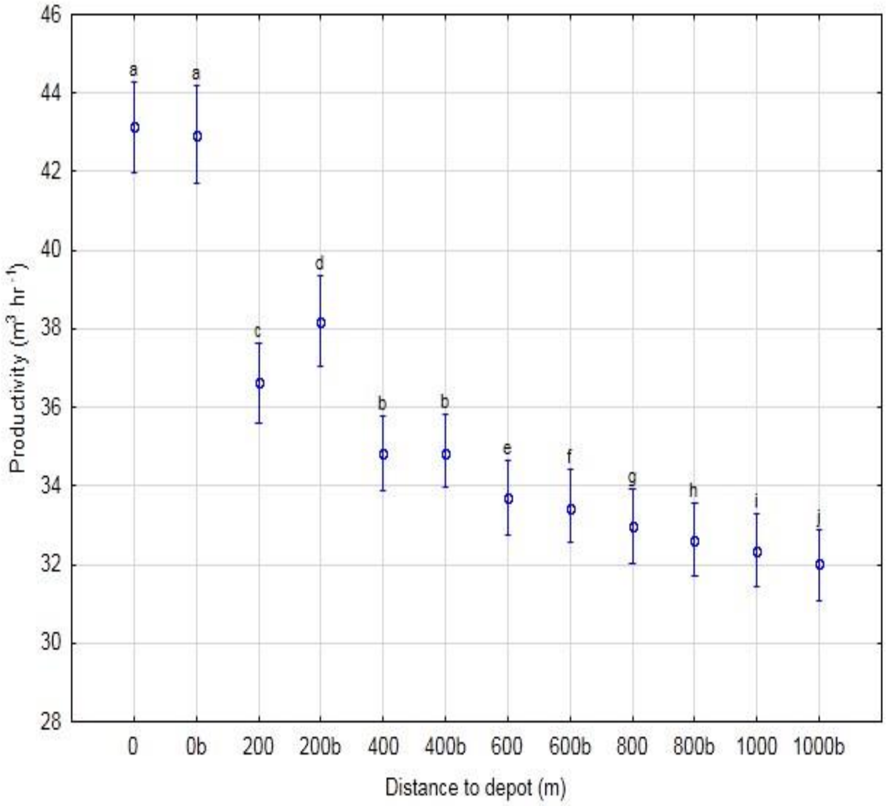

Figure 26: Bootstrap means of forwarder productivity when extracting to increasing depot distances using a larger grapple on a 95% confidence interval (letters that differ indicate significant difference, distances marked with a "b" indicate instances of forwarding in B-A direction).

Scenario 5: Simulation output of the forwarder extracting log assortments using only one road (road on the north-eastern boundary of the compartment) indicates significant differences in productivity between the on-road distance intervals 0 m, 100 m, 300 m, 500 m and 700 m when using the standard grapple. Significant differences in productivity are noted at the on-road distance intervals 0 m, 100 m, 300 m and 500 m when using the larger grapple. No significant differences in productivity are noted for the distance interval 900 m when using the standard grapple, while significant differences are noted at the distance interval of 700 m when using the larger grapple.

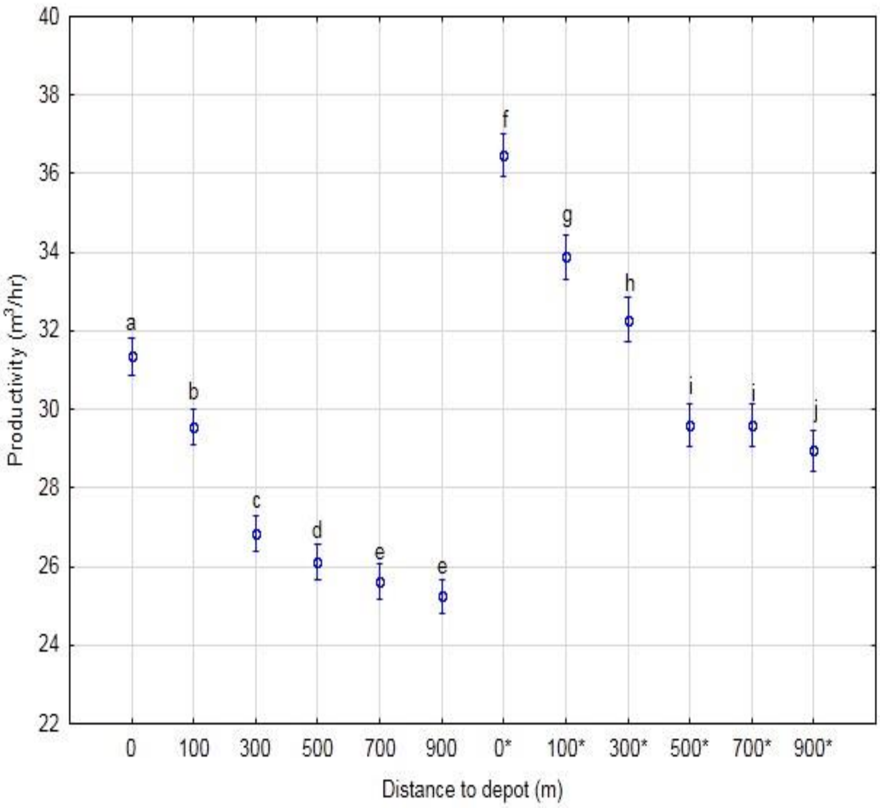

Figure 27: Bootstrap means of forwarder productivity when extracting to increasing depot distances using both grapples and a single road on a 95% confidence interval (letters that differ indicate significant difference, * indicate scenarios where large grapple was used).

5. Discussion

Time study and system observation

Time studies are carried out for only a relatively short period of time, and therefore only represent a snapshot of the possible variation in work element times that can occur within the observed system.

The site itself, although not uncommon for South African conditions, most likely also plays a role in the outcome of the study. A site containing more uniform trees, uniform in the sense of similar DBH and height ranges, as well as form throughout the stand may yield vastly different results, other than the observed site. Factors other than site that could influence the degree of variation of the observed system productivity are: weather conditions, different tree species, site conditions and even the machine operators.

It should be kept in mind that this study's objectives are not to represent the system as a whole, but to rather simulate each machine individually for the period of time required to harvest and extract a virtual version of the study area. This study could be classified as a repeated measures experiment.

Alternative harvesting and extraction scenarios

Scenario 2:

With regards to scenario 2, the current operating practice of felling alternating swaths of four and five trees wide yielded the highest productivity and lowest cost. However, even though the Bootstrap test shows there is a significant difference between all three swaths (four-tree-wide, five-tree-wide and the combination), the actual difference in productivity is minimal. In reality all three of the swath sizes return an average productivity within 1 m^3 hr^{-1} of each other.

Differences between felling and processing a wider swath (i.e., swaths of only five trees wide) may in fact be more productive as more trees are felled and processed before moving to the next setting. However, due to the simulation using input data generated from theoretical distributions that contain wide variation and not a more predictive approach (linear models based on input data) it is difficult to say as each run of the simulation is going to yield varying results with regards to productivity.

Factors such as linear boom distance and angle to each tree could have a significant effect on the time consumption and therefore the productivity and cost. Eliasson and Lageson (1999) stated that “a simulation must model a harvester’s motions accurately and these motions must interact with the environment”. The harvester’s movements in this study were modelled in detail. However, as mentioned previously the large variation in the time study data could not be used in order to create suitable time consumption models, capable of using the detailed input data (angles, boom distances and tree volumes). Hence randomly generated times had to be used.

Naturally it seems sensible that when a tree located further away is to be cut, the time it takes for the harvesting head to reach that tree is longer than the time required to reach a tree located in close proximity to the harvester. This was not true for the observed harvester. When a tree was located further away it seemed the operator was able to reach the tree quicker and position the head faster. This seemed to be achieved by the operator felling the trees directly in front of the machine effectively opening up a gap three trees wide, minimizing manoeuvring time as there are no obstructions (trees) to work around. This led to the situation where trees located further away have similar harvesting times to trees located nearer to the machine.

Another assumption made is that larger trees take longer to fell and process as opposed to smaller trees. This was not the case in this study. The operator appeared to take longer to position the head when trees were of a smaller size or when they had poor stem form.

A final comment to make with regards to felling different width swaths concerns the operator. The observed operator was said to be experienced, however, each operator will work with a different method. Studying a number of operators working in the same stand and across other stands could have showed trends different to those observed in this study. Previous studies have shown that productivity levels can vary up to 40% between operators (Ovaskainen et al., 2004).

If the data had allowed for predictive time consumption models, the harvester’s boom movements could have been extensively experimented with, in order to study the effects of harvesting the widest swath possible, as well as narrower swaths. Different felling patterns could also be tested (i.e., the order in which trees are felled).

Figure 28 is a scatter plot showing the time consumption as a function of linear boom distance. Figure 29 on the other hand shows the lack of trends between boom extension time and tree position in relation to the machine (angle from harvester to tree). This effectively shows that work element time consumption was not affected by the row in which the harvester was working. It must be kept in mind that the angles shown in Figure 29 are the actual positions of the trees in a 180° arc. Swaths were not planted in straight lines in the observed system, there was a slight curve to them (Figure 17). This was recreated in the virtual stand, therefore some trees were located at angles greater than 180°.

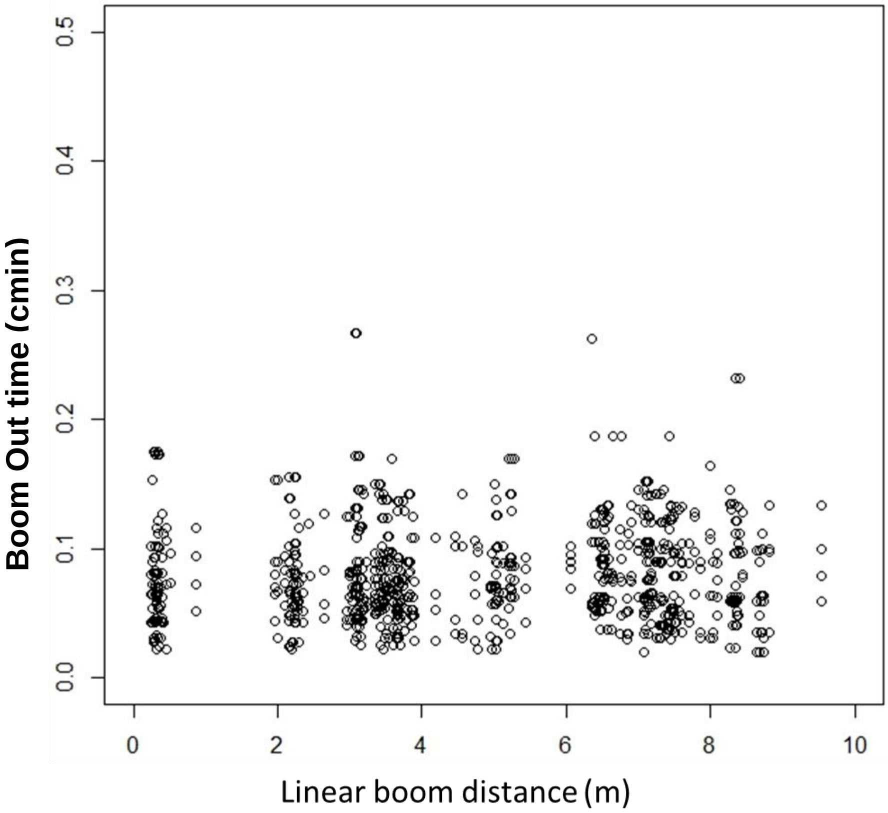

Figure 28: Indication of lacking trends between linear boom distance and boom out time.

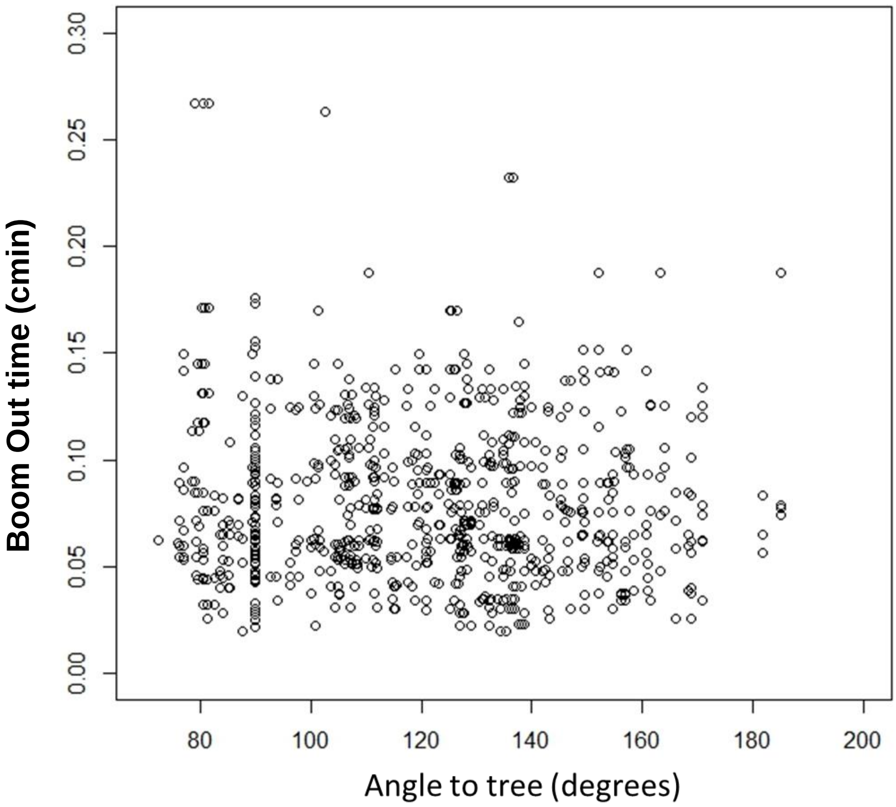

Figure 29: Indication of lacking trends between row harvester works in and work element time.

Scenario 3:

It is evident that each tree size class that was tested had a significant effect on harvester productivity both statistically and practically. This is in agreement with other studies by Eliasson & Lageson (1999); Väätäinen et al., (2004); Nurminen et al., (2006); Väätäinen et al., (2006a); Nakagawa et al., (2010); Magagnotti et al., (2011); Visser & Spinelli (2012); Walsh & Strandgard (2014) that studied cut-to-length harvesting operations. The authors found tree size had a significant effect on harvester productivity and that increasing tree size leads to greater productivity. The above mentioned authors also found that tree size had a significant effect on felling and processing work element times. One of the reasons for the lack of this trend in this study is due to the use of random probability distributions. The distributions that best fitted the felling and processing work elements are used to model these activities for all three tree sizes, therefore a larger tree may receive a time below what may actually be required and a small tree may receive a disproportionally longer time than required. Another reason is due to the current harvesting practice of debarking eucalypts completely in-field. *E. smithii* when harvested during the winter months can be difficult to debark. This led to the case where the larger trees were easier to debark and therefore had a lower processing time and smaller trees were more difficult to debark causing them to have a longer processing time.

With the results of scenario 3 showing productivity increasing with an increase in individual tree volume it is important to note that the input data showed no trend when looking at the relationship between individual tree volumes and the harvesters work element times. This finding goes against other studies (Spinelli et al., 2002; Wang et al., 2005). The most likely reason for this result is due to the many stem deformities and large variation in stem size and tree height.

Table 20 does not include the work element time changes for all work elements, as the times were modelled using random probability distributions therefore there is no meaningful difference as the effect of tree size on work element time cannot be seen.

Many factors concerned with scenario 2 are applicable to scenario 3 such as operator’s working method and more importantly tree deformities. These were found to compound the difficulty of felling and processing larger trees. Hartsough and Cooper (1999) were able to identify an additional amount of processing time consumed when trees contained forks and crooks along the stem. This was the case with a large percentage of the trees found within the study site. This has most likely led to large variation in the felling and processing times as has the difficulty of debarking the logs. The large number of smaller diameter trees could also have had a negative effect on the harvester’s productivity as it is much more difficult to handle and debark smaller sized stems as the harvester’s head is tailored to work with slightly larger trees from 15 cm – 40 cm DBH (SP-Maskiner, 2014).

With regards to the forwarding of larger volume stacks using both the standard size grapple and the larger grapple, the relative insignificance of forwarding direction (either A-B or B-A) can possibly be explained due to the various travel speeds of the forwarder (Table 22).

Table 22: Forwarder mean travel speeds calculated using linear models found in Table 10.

Travel element	Mean travel speed (m s^{-1})
On-road empty	2.21
Off-road empty	0.50
Off-road loaded	0.40
On-road loaded	2.50

According to the time study data the forwarder travelled at higher speeds when fully laden towards the depot versus travelling empty from the depot (Table 22), this can possibly attributed to operator comfort. When empty the forwarder bumps around violently at higher speeds whereas when fully laden the forwarder is more stable. The inability of the linear models to explain some of this variation that occurred compounds the problem. It is evident that the road running along the south-western edge of the compartment contained more corners versus the road running along the north-eastern boundary (Figure 17). This could have reduced the speed at which the forwarder travelled. During observation of the machine most of the forwarding was performed in the pattern indicated in Figure 17, therefore there is no real representation of the forwarder travelling fully laden along the top road to the depot.

Possible reasons behind the 3.6 m^3 stacks having the lowest productivities with both grapple sizes could be attributed to the amount of timber extracted per cycle. As previously mentioned, the number of stacks extracted per cycle was randomised to avoid overloading the forwarder where possible thus increasing the number of trips the forwarder made. This randomisation led to the average volume of timber extracted per cycle dropping from 15.8 m^3 $cycle^{-1}$ to 15.3 m^3 $cycle^{-1}$. This value in reality would most likely be greater than 15.3 m^3 $cycle^{-1}$, as larger trees when loaded will have a lower airspace loss factor. Therefore a larger volume will be present on the forwarder leading to a greater mean productivity.

It is evident from the data gathered during the time study that the forwarder is able to load and unload larger volumes easier and faster. This result is also found to be true by McNeel and Rutherford (1994); Wang et al (2005) and Nurminen et al. (2006). The authors found productivity of the forwarder increased with an increase in log volume and stack volume.

Under the assumption that the forwarder would have to make more trips to the depot when forwarding the larger stack sizes, repeated use of the same tracks when extracting via the use of the single road extraction scenario, could lead to site degradation as was found in Han et al. (2006).

Scenario 4:

As previously mentioned the linear models used to calculate the travel speeds of the forwarder (Table 11), the difference between predicted speeds and speeds of the observed machine had a large amount of unexplained variation. The road layout may have affected speeds when travelling empty and loaded. The use of models that have a relatively poor R^2 still identify the trends of the forwarder travelling faster when loaded, as well as the mean speed being higher when the distance of road travel increased. These trends are found in a similar study by Nurminen et al. (2006).

A distinct decrease in productivity is evident when looking at both Figure 25 and Figure 26. The smallest drop in productivity is found between distance on-road travel intervals 800 m and 1000 m, with a decrease in productivity of 1.6% when using the standard grapple and 1.8% when using the larger grapple. The largest decrease in productivity is found between the on-road travel distance intervals 0 m and 200 m, with a decrease in productivity of 15.3% when using the standard grapple and 17.8% when using the larger grapple. This result is supported by Nurminen et al. (2006) who found that forwarder productivity decreased by up to 14% when extraction distance increased by 200 m.

The maximum on-road distance the forwarder travelled during the time study was 497m, therefore simulation of distances greater than this relied on extrapolation of work element times and this process is known to return results that may differ from reality.

Data collected during the time study could have described more variance if more stands were incorporated into the study. However, this was not possible as there were no similar stands being harvested. Studying various operators during different shifts could also have helped to explain some of the large variation encountered in the model. Nurminen et al. (2006) experienced very similar problems where few sites were observed as well as limited operators, therefore providing only a snapshot view of the operation. In the study it was stated that more stands and operators should be studied for greater accuracy and the ability to apply models to stands in different locations.

Scenario 5:

Scenario 5 and scenario 4 share many similarities with regards to the final results. Forwarder productivity decreases with an increase in forwarding distance. Where the smallest decrease is found between the last two distance intervals (700 m and 900 m). A productivity decrease of 1.5% was found when using the standard grapple and a decrease of 2.2% when using the larger grapple. The greatest decrease in productivity is found between the on-road distance intervals 0 m and 100 m, with a decrease of 6.1% when using the standard grapple and 7.6% when using the larger grapple. These distances exhibited lower drops in productivity most likely due to the distance increasing to 100 m instead of 200 m. The reason for this is that the point of entry into the compartment is on average 100 m closer to the depot than the equivalent entry point located along the south-western road. This method of forwarding would increase traffic intensity on the site as the forwarder is now travelling the same path twice for every cycle, a conclusion also noted in Wang et al. (2005).

Methods used to simulate the various harvesting and forwarding scenarios are based strongly on the observed machines operating practices. This is not ideal when wanting to apply the results of the simulation to other stands. However, this study is still important as it highlights the potential problems that can be encountered when trying to study a relatively poor stand. The disadvantages of studying a stand with a large percentage of deformed trees and large size variation are quite clear. Simulations based on data collected from these stands need to be supplemented with a vast amount of additional data, to try and explain some of the variation encountered with such stands. By explaining more of the variation encountered, a more predictive approach can be taken and most importantly the accuracy of these predictive models can be improved significantly.

Simulating with R

R has the ability to carry out simulation projects, however, there are some shortcomings with using the software. A major shortcoming is the inability to precisely match input data time distributions to theoretical probability distributions. This problem can be overcome by using the next best fitting distribution. However this leads to certain inaccuracies during the simulation and the results may deviate from real world values as they did in this study (Table 17). Although this is a major pitfall with the software, it can be overcome as it is possible to create packages that contain functions. It is possible for someone to write a package containing certain theoretical probability distributions commonly used in simulations such as the Erlang, Gamma, Continuous, Triangular or Johnson distributions (Kelton et al., 2003). Packages written and submitted by users are peer reviewed before being released for download. Such a solution is however outside the scope of this project.

The lack of comprehensive menu based functions creates the scenario where simple functions and tests can be time consuming to prepare, as the user must write the code and define all the necessary parameters. To aid users with no prior programming experience the programme has a package called Rcmdr (R commander) (Fox, 2005). This package provides a command window with a limited number of dropdown menus containing the most commonly used functions and graphs. The R Commander works by having a data set imported and selected as an active input sheet. Once a function is selected from the menu the code is generated and is available for modification. The only problem noted when using the R commander is the inability to handle large data sets. When a large data set is set as active input the programme often crashes therefore it was not used for the purposes of this study.

Animated graphical representations of the processes occurring during the simulation are very demanding on the processing power of the user’s PC. These animated graphical representations of the simulations can be programmed but are quite complex and time consuming to develop. The programme is not tailored to forestry therefore the graphical outputs may be simplistic. The ability to use real world sites and other geographical information relating to each site would be a benefit. Packages are available that contain functions that are able to model detailed site characteristics and display these in either three-dimensional or two-dimensional output. These detailed site graphics will be associated to some input data, this input data can be used to calculate some of the supplementary data required to improve the fit of models and make the simulation more realistic in general. This study made use of geographical data obtained by applying certain functions to a shape file imported into R as discussed in the methodology of this study. This data was then fed back in as supplementary data and used mainly for machine travel calculations.

The flexibility offered by R is a redeeming characteristic in that each simulation can be tailored to a specific compartment or specific method of harvesting for example. This characteristic sets it apart from conventional menu based simulation programmes such as Arena and Simio, which have a strong focus on the manufacturing industry. It is sometimes hard to apply these simulation components to forest operations as forest operation processes do not occur in the same location, for example: the resource (machine) moves to the entity.

If the input data collected shows distinct trends and linear modelling potential Simulation using R can be performed easily. Non-linear regression in R is complex to perform and requires a high level of user competency, for this reason R cannot be seen as highly suitable simulation software.

Bootstrapping of simulation output data

When using the Bootstrap method of statistical analyses, very small differences were detected between treatments at the 5% level. These differences which appeared statistically significant were in some cases very small changes in productivity. However, it should be kept in mind that these changes in productivity add up over the full length of a shift, especially if the avoidable delays can be removed to a large extent.

6. Conclusions and Recommendations

A study of two mechanised cut-to-length harvesting machines, namely an excavator based harvester and purpose built forwarder was carried out in the vicinity of Richmond, Kwa-Zulu Natal.

Sub-objectives of the study were:

I. Determine the applicability of using open source software (R) for accurate discrete-event simulation modelling of forest harvesting operations.
II. Gauge potential machine work method optimisation and/or cost reduction using simulation-based operational adjustments.
III. Attempt to account for the impact of large stand growth variability on productivity and cost.

In terms of the study's main objective, the cut-to-length harvesting machines were simulated with varying degrees of accuracy. Quality of the input data appeared to have the biggest effect on the degree of accuracy to which the two machines could be simulated.

The use of R for discrete-event simulation was met to a degree. R software is suitable to an extent, for use as a discrete-event simulation platform. However, there are some modifications that are needed before it can be said that R is a highly suitable simulation software package. The ability to incorporate spatial features into simulation models and the general flexibility offered makes R a suitable simulation software to experienced users however vast amounts of effort are required. The fact that R is open source software (free to download and use) is also beneficial, especially to users that do not wish to purchase licensed software.

Through R, simulation of the current machines' operating practices and operational changes to these practices, it was possible to reduce operating costs and improve productivity of both the harvester and the forwarder to an extent. Alongside this, it was possible to show the combined effects of tree size and debarking difficulty on the harvester's productivity as well as the effect of extraction distance on the forwarder's productivity. When forwarding via the two-road system, an on-road forwarding distance increase from 0 m to 200 m led to a decrease in productivity of

15.3% when using the standard grapple and 17.8% when using the larger grapple. The increase in on-road forwarding distance from 0 m to 200 m was the largest reported decrease in productivity. When forwarding using a single road, the largest decrease in productivity was found between the on-road forwarding distance intervals 0 m and 100 m, with a decrease in productivity of 6.1% when using the standard grapple and 7.6% when using the larger grapple.

Fitting a larger grapple (1 m^2) had a distinct benefit to the forwarder's productivity especially when forwarding larger stacks. Increases in productivity of 14.48% (2.5 m^3 stacks), 14.65% (3.6 m^3 stacks) and 15.85% (5.4 m^3 stacks) were noted when using the larger grapple as opposed to the original grapple (0.8 m^2). The process of double stacking should be maintained as stacks of larger volume have been proven to yield better forwarder productivity (Figure 24).

The results presented are based only on a representation of reality. Therefore there may be a degree of inaccuracy to them. However through use of the correct probability distributions and predictive models with lower variation, it is possible to get more accurate predictions regarding productivity and cost. The fact that the results of both machines matched distinct trends found by other authors proves that, even when not highly accurate at this point in time R is suitable for simulation purposes.

Thirdly, a difference between simulating a stand consisting of many poorly formed trees and a stand consisting of straight, even-sized trees has become evident. The "poor stand" requires a great amount of supplementary data in order to try and remove some of the variation from models. It was also noted that the "poor stand" has a considerable effect on the harvester and a smaller effect on the forwarder. Stands with poor stem form and difficult debarking conditions require harvester operators with a high level of competency to counter the negative effects that the stem deformities and debarking difficulties have on the production rate.

Finally, the availability of both built in and online help files, most complete with example data sets and functions allow the users to obtain help easily, creating a relatively easy to use program. The availability of online help forums allows for more in depth help as users can post questions relating to the simulation at which point another user with experience will be able to post a method to overcome the problem.

Numerous books are available containing code for common functions and specifically graphical outputs. All these points allow for a relatively easy to use simulation programme.

Some recommendations that can be made for future studies of similar sites:

I. If a stand of poor form is to be studied, more than one site must be incorporated into the study.
II. Multiple operators should be studied, to study the proficiency of dealing with stem deformities.
III. Supplementary data must be collected for all machines in the study.
IV. Record the operations on video when performing the time study for future reference.

Recommendations that can be made concerning the machines studied:

I. Felling alternating swaths of four and five tree wide swaths should continue and the operators should continue to double stack the timber.
II. Stands containing larger tree sizes should be scheduled for mechanised cut-to-length harvesting.
III. Where-ever possible the harvester operator should try to harvest as many trees as possible from each position, in order to create larger stacks for the forwarder.
IV. Forwarding should not include any road travel. Timber should be forwarded to roadside only.
V. Forwarder should be fitted with the largest possible size grapple, but match the piece size being loaded.
VI. Automated recording software should be fitted in the forwarder so that the operator does not need to manually record the load count.

Further recommendations include the writing of a package that can be added to the R library containing all necessary distributions used in simulations. More simulation studies need to be carried out using R in order to test different scenarios and further identify potential weak spots within the software.

Studies of other typical South African harvesting operations such as harvesting on steep terrain, using both cable extraction systems and purpose-built cut-to-length or full-tree systems should be conducted. Studies concerning focusing on the entire tree-to-mill value chain need to be carried out.

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