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Defining options to reduce tree harvesting costs on steep slopes

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CLIENT REPORT – DRAFT FOR REVIEW

Defining options to reduce tree harvesting costs on steep slopes

Sarah Heine and Dzhamal Amishev

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REPORT INFORMATION SHEET

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EXECUTIVE SUMMARY

The forest harvesting operation contributes to approximately 50% of the cost of wood production in New Zealand, representing one of the highest harvesting costs in the world. The proportionate cost is even higher on steep country, typical of much of New Zealand's plantation estate. Unchecked, these costs are likely to increase as the prices of labour and fuel rise, and as forest management practices change due to the impact of factors such as the Emissions Trading Scheme (e.g. longer rotations and less silviculture).

This purpose of this project was to address the issue of high costs by producing a dynamic-systems model of the harvesting process. Such a model can be used to define factors having a large influence on harvesting productivity. This knowledge can help to identify opportunities for short term improvements in harvesting methods. The model may also be used to evaluate the potential for long term step-change approaches to harvesting on steep sites. The model synthesises the full harvesting operation in such a way that all its components can be analysed to define opportunities for reducing costs and enhancing productivity.

Under this contract, Scion has succeeded in developing a New Zealand-specific forest cable harvesting system, which is understood to be the first of its kind in the world. The exercise of model development clearly identified many shortcomings in data collection and variable description that limited the usefulness and applicability of the proposed modelling approach. Nevertheless, we were able to conclude that:

1. The systems model provides a reasonable representation of cable logging as typically carried out in New Zealand. This model will be constantly improved with increasing amounts of information and developing productivity relationships through ongoing research efforts in New Zealand and internationally.

2. A sensitivity analysis of the system provides pointers to direct future research, particularly the need for improved data collection and methods to describe and quantify the interrelated variables within a harvesting system.

3. The model provides a good starting point for identifying critical areas where operational, systems or human productivity interventions could lead to improved overall productivity. Initial results suggest that with cable extraction, it is most likely that the hauler is the productivity bottleneck within the harvesting system. Therefore, only those parameters that directly impact the hauler productivity are the critical elements that determine system output.

This project provides a basis for further research aimed at transforming harvesting systems. The ultimate aim is to create systems that reduce the problems (economic and social) associated with steep country harvesting and that also reduce death and injury in this dangerous operation. A reduction of every $1 per tonne in harvesting cost would equate to an additional $25 million (approx.) of value per annum and make New Zealand forestry more internationally competitive.

Such improvements will encourage an increase in reforestation on steep country, which will assist with both the climate change plan of action, and further produce environmental and economic outcomes for the benefit of New Zealand.

Defining Options to Reduce Tree Harvesting Costs on Steep Slopes

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31 March 2010

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Introduction

Among the world's major wood producers, New Zealand has the third highest harvesting cost per tonne (IWMR, 2005). Logging flat land in New Zealand costs $24 per tonne on average and for steep land it averages $38 per tonne(AGRI-FAX, 2007) (data from 2005). By comparison, Sweden's average harvesting costs are about $10 per tonne (Bergkvist, 2006). Although most of this harvesting is on flatter land, Swedish producers achieve substantial savings by employing a much greater degree of mechanisation.

Overseas forestry operations typically harvest smaller trees on flatter land than in New Zealand. We therefore struggle to capitilise on research gains made in other countries as their systems and technologies cannot be readily adapted to predominant New Zealand conditions. There are several highly linked and interactive components to the harvesting process, including:

- human performance;
- equipment;
- material flow;
- infrastructure;
- transportation; and
- log processing.

The complexity of the interactions highlights the need to understand the impact of any given change within the system and on the overall process. The research conducted in this project provides a basis for identifying new methods or technologies that can be used to improve the economics of harvesting on steep terrain.

Steep harvesting methods

Steep country harvesting in New Zealand currently uses cable logging, which is a very labour intensive operation. It consists of a large cable secured at an elevated skid site with the other end secured at a pivot below in the forest (Fig. 1).

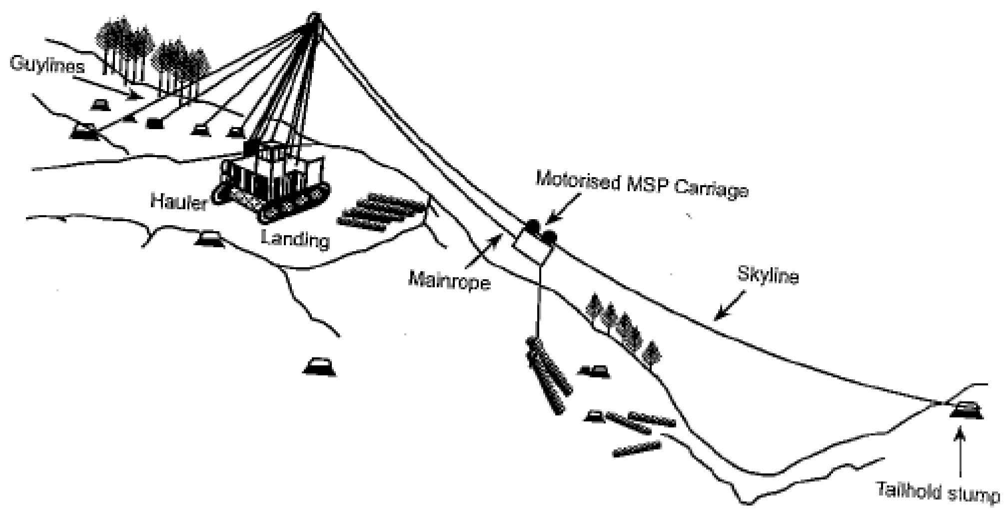

Figure 1. Illustration of a standing skyline (cable) system with a motorised slack-pulling (MSP) carriage.

When the trees are felled they are attached to the cable, winched to the skid, sorted, passed on to the log makers, and then transported to the mill. The difficult terrain, large distances and the need for remote control, coupled with the dangerous and physical demands on the operators, make this an expensive, risky and highly interactive operation. For example, a small delay in clearing the logs from the log makers can stop the entire operation including tree felling. Predicting the performance of harvesting systems is a difficult task particularly as there are many cable logging systems in operation (Fig. 2). Within each category of cable logging systems, numerous alternatives and possible machine combinations exist. The machines themselves are also very complex. They operate in a constantly changing environment where they interact with other machines and are influenced by a range of site and stand factors. While the potential of an individual machine can be quantified through production studies, the effects on productivity, from a variable environment and interactions with other machinery, are more difficult to gauge (Gingras, 1989).

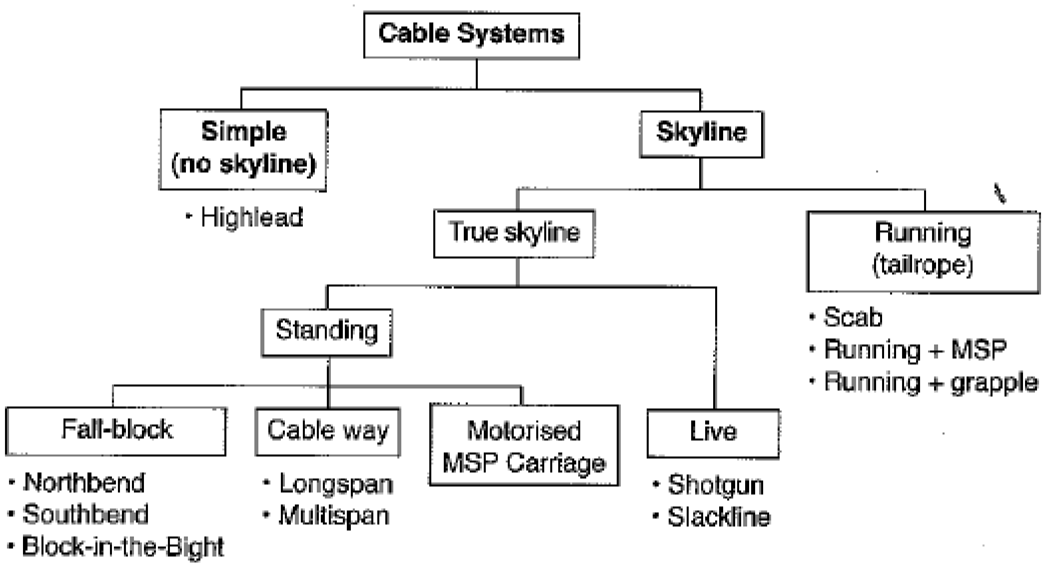

Figure 2. Categories of cable logging systems (FIT, 2000).

Forest harvesting and modelling

Computer simulation of logging systems began in the late 1960s. The goal of most logging system simulations has been to determine productivity, costs and the effect of changes to the system on productivity and costs. The scope of existing forest harvesting models can be grouped into four categories (McDonagh et al., 2004):

1. Single machine (Greene and McNeel, 1987) – These models include highly involved simulations of the activity of a machine and the interaction of a machine with site and stand parameters.
2. Multiple machines/in-forests system (McDonald et al., 2001) – These models typically lose some of the detail in the simulation of the individual machines, however the general complexity of the model increases when the issue of machine interactions is introduced.

3. Transportation system (Barrett, 2001) – A deterministic approach to truck scheduling for harvest system models can capture impacts of trucking without interfering with the harvesting model.
4. Tree-to-Mill systems (Goulet et al., 1979a) – These models recognise the importance of all aspects of the supply chain from the forests to the consumer.

Data capture

As with all models, an effective and useful harvesting systems model will depend on the quality of the input data. Data were required from all elements of the harvesting system to develop the model described in this report. Data capture was impacted by two key issues:

1. The time consuming nature of data capture. Data inputs required are varied in both type and detail and may require extensive field work to obtain (Goulet et al., 1979a). The complex nature of harvesting data collection is exacerbated by remote locations, rough terrain, a diverse work force and multiple human/machine interfaces.
2. Each harvesting situation is unique, and there are a number of factors influencing performance that vary constantly within each situation. Unlike most manufacturing processes, timber harvesting systems operate in a dynamic environment that changes with each harvest undertaken. Consequently, harvesting production is as much a function of timber-stand and harvest-site attributes as harvest system configurations.

In this project, the first issue has been partially addressed by the use of a different data capture technique, particularly a unique audio and visual data capture method developed by Scion (Parker et al., 2009). This method allows a number of attributes to be measured by recorders worn by the worker while performing tasks, meaning that the researcher does not have to be physically present and observing at the time of data capture. This approach allows the researcher to achieve a much higher rate of data capture, as a number of the crew can be fitted with data capture hardware at any one time. It also addresses the inevitable change in performance when an individual is being, and is aware he is being, observed. It is human nature under such conditions for workers to perform differently from the way they may act when operating on their own and unobserved, therefore providing skewed data.

The second issue is far more difficult to address when attempting to analyse crew productivity. The interactions of site, crop (size, variation, form etc), cut-plan, terrain, machinery, staff and management mean that at any given time during production the situation is unique. The factors impacting on production are likely to be only partially measurable, and therefore only partially or not taken into account at all, when assessing what has driven production. The inherent variability in harvesting system configurations, operating environments and potential interactions between system components, make attempts at modelling these systems very challenging (Sterman, 2000). When using any model to examine a specific situation in harvesting, use of judgement based on personal experience of the particular crew and knowledge of local conditions is imperative. A brief summary of key factors influencing variability follows.

Site factors

Site factors that affect productivity can largely be measured, although some will be difficult to classify accurately enough to allow data from a number of sites to be merged. One example is gradient, which can be measured for each setting, which is the area logged to one hauler set up. However this variable is generally captured as an average over the setting and will not take account of the variability within the setting. Gradient may be recorded as average slope or as a class variable (for example percentage flat, percentage flat to rolling, etc). When comparing data from different sources such classification is likely to vary between companies and even within companies depending on staff.

Soil type, affecting site accessibility as well as movement speed of forestry machines, is also likely to impact on productivity but does not often appear to be recorded. Hindrance such as cliffs, drops, boulders, stumps and logs from previous crops are also difficult to measure but can significantly influence productivity. Other factors such as the size of the landing, the haul distance and access to the backline also influence productivity. Such factors may alter constantly over time, with available landing size, for example, being affected by the initial size constructed, the original layout, and the number of log stacks. The number of stacks will in turn be impacted by the type of available machinery being used; whether processing is mechanical or manual; availability and timing of trucks; frequency of cut-plan changes; and the ability to rotate stocks to ensure freshness of wood.

Crop attributes

Within production forest estates, crop attributes are usually measured. However, the level of tree variability within a stand will result in production fluctuations. Factors such as stocking, piece size and branch size will affect production, and while these data are available, the level of variability of such attributes within the stand is unlikely to be known.

Equipment factors

Machinery used by a crew can be easily measured at a point in time. However the specific machinery may vary within a crew and a setting. Logging contractors often have a number of crews and may shift machines between them as required or available. Machines may be brought in to perform a specific function such as felling trees close to the landings edge if the terrain is suitable and then removed once the specific task is completed. Often the number of machines may be captured but not the specifications of the machines (e.g. size of excavator or specific model used).

People

Staff performance within a crew will contribute to productivity in a number of ways. The experience, motivation, and ability of the operator, both in mechanised and manual tasks will have a big impact on performance and is difficult to record. As stated in one study, operator skill is found to be a prime determinant of productivity for all machine classes (Anderson and Young, 1998). Research studies on productivity may record some of this information but crew productivity data captured by companies are most unlikely to include such details. Experience can influence everything, from landing set up, crew dynamics and harvesting system down to individual task performance. It may dictate where certain machines will operate, with different operators comfortable to work on different slopes and will almost certainly dictate how effectively and safely they can perform their role. For some people experience is not a substitute for skill level or productivity as some people will naturally perform better at a given task then others.

Aside from experience, with any workforce there will be day to day variations depending on their mood, health and any number of other factors that drive human performance (Fig. 3). In the case illustrated, the operator started with no experience and over the 400 measurement days there was significant improvement. However during the study there was a high level of variability observed, with explanations provided when there was an obvious reason affecting productivity. These causes ranged from external factors such as site (heavy slash), crop (double leaders, big branches), machinery (chain falling off frequently) or operator (working long hours, injured finger). There were times when the productivity fluctuated without explanation and these changes may have been due to influences outside of work (e.g. operator tired for “other” reasons, operator preoccupied with external factors, operator just having a bad day). Given that a logging crew often carries more than nine staff, where roles are often interactive within the harvesting system, then staff variability is likely to be a significant factor in crew productivity performance. This cause is almost impossible to measure and quantify.

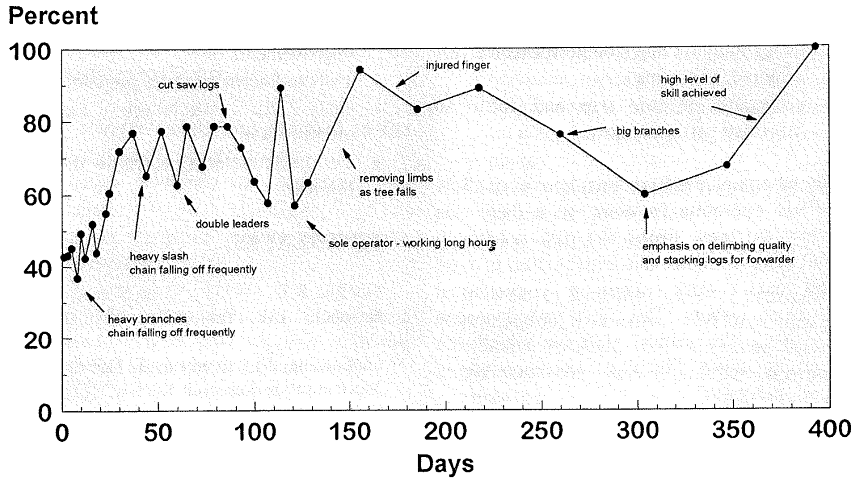

Figure 3. Harvester productivity learning curve (as a % of the most productive day) (Parker et al., 1996).

The characteristics of a top performing crew as listed in the Business Management for Logging Handbook (BMLH, 2009) include:

- A respected leader with an interest in the workers
- Clear goals, performance standards and expectations of productivity and equipment maintenance.
- Good work planning and high job flexibility.
- Each crew members given individual accountability for safety and equipment, and all crew members have clear roles and responsibility.
- Equipment that is suitable for the task and well maintained.

Even though some of these attributes can actually be measured in a given situation, what is more difficult to ascertain is the level, extent or degree to which such tasks are implemented. What is clear is that management of the crew will play an important role in performance, and the extent of this is almost impossible to quantitatively measure. With the very fact that harvesting business performance has traditionally only been associated with the quest for productivity, lower costs may in fact be affecting their ability to deliver high output.

The introduction of a broader and more comprehensive definition of Forest Harvesting Entrepreneurs (contractors) brings about a significant shift in perspective in forestry research. A greater willingness to engage in research can lead to innovative progress that will improve their performance and more generally, that of the forest supply chain (Drolet and LeBel, in press). By using some of the tools used by Small and Medium Business (SME) such as entrepreneur motivation, management habits and attitudes, business strategy and other non-financial dimensions, overall performance can be enhanced (Lebel and Stuart, 1998; Makinen, 1997).

System dynamics modelling for harvesting steep slopes

System Dynamics is one approach to modelling the dynamics of complex systems such as population, ecological and economic systems, which usually interact strongly with each other. It is a method to understand how complex systems change with time, allowing the influence of internal feedback loops within the system to be determined. Harvesting logs on steep slopes is an excellent example of a complex system that is suited to this modelling approach.

System Dynamics was founded in the early 1960s by Jay W. Forrester of the MIT Sloan School of Management with the establishment of the MIT System Dynamics Group. There are two main components of a system dynamics model:

1. Causal Loop Diagrams (CLD) which show the causal influences between sets of two variables linked by arrows. Each causal link is associated with a polarity (positive or negative), expressing the influence of independent variables on the dependent one. The result is the creation of feedback loops that may represent positive or negative feedback.
2. Stocks and Flows. A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in a stock. A stock and flow diagram shows the accumulation or depletion of a stock over time.

Computer software is then used to simulate a system dynamics model, which allows the behaviour of the system to be studied under various scenarios. The steps involved in a simulation are:

1. Define the system boundary.
2. Identify the most important stocks, and flows that change the stock levels.
3. Identify sources of information that impact the flows.
4. Identify the main feedback loops.
5. Complete a causal loop diagram that links the stocks, flows and sources of information.
6. Obtain the equations that determine the flows, whether through data analysis or from literature information.
7. Determine the parameters and initial conditions from statistical methods, literature or other sources of information.
8. Simulate the model and test against calibration data.

For many years, cable logging has remained the only method for harvesting on steep slopes (Terlesk, 1982). Small changes in harvesting costs could substantially improve the viability of forestry in such arease thus providing the economic incentive to expand into what has been classed as marginal land. The aim of this study was therefore to develop a model that could provide estimates of harvesting system productivity on steep slopes and the associated costs of this production. This information would then be used to analyse the impact of different man/machine combinations on the cost of production and the impact of new technologies and practices aimed at reducing that cost of production.

The underlying hypothesis of the research is that cost and productivity improvements can be made in cable harvesting by:

1. Breaking down the operation into discrete units and through application of causal loops understand how each sub unit interacts with the whole system.
2. The ability to translate good practice in one part of the operation in one crew to another crew.
3. Using the dynamic systems model to test both the potential impact of small and large changes to the operation.

Given the complexity of the harvesting process, this first attempt to develop a system dynamics model for the New Zealand situation was focussed on the cost to get the wood processed and stacked on the landing. Many other factors could be included in future iterations, including the impacts of stock held, trucking frequency/timing, and the cost of getting crew and equipment to site.

Methodology

Data collection

Three different data sets were required for model development: industry data, validation data, and literature data.

Industry data

A number of companies were approached in confidence to supply both numerical and qualitative information on (i) how they viewed their contractors, (ii) why they collected the particular data and (iii) why they did not record or seek any additional data. Four companies supplied data for the project. All were in the top 15 owner / management companies in New Zealand by area (NZ Forest Industry Facts & Figures 2008/2009). All were from different areas around the country and all operated over a range of terrain classes. The data differed between the companies and was merged where possible, and appropriate, to study the relationship between the factors impacting on productivity rates.

Validation data

Individual crew studies were conducted to provide data to test the model. Three crews were selected, two from the North Island and one from the South Island. To maintain confidentiality, all information that could identify the crew has been omitted from this report. For each crew, between three and five days were spent on site gathering information on productivity and performance, and various aspects of the harvesting system.

Audio and video equipment was utilised in the field and the data were analysed using specific hardware and software (Fig. 4). This technique maximised the information collected for the time spent, and allowed productivity calculations to be performed on both bunched and unbunched wood.

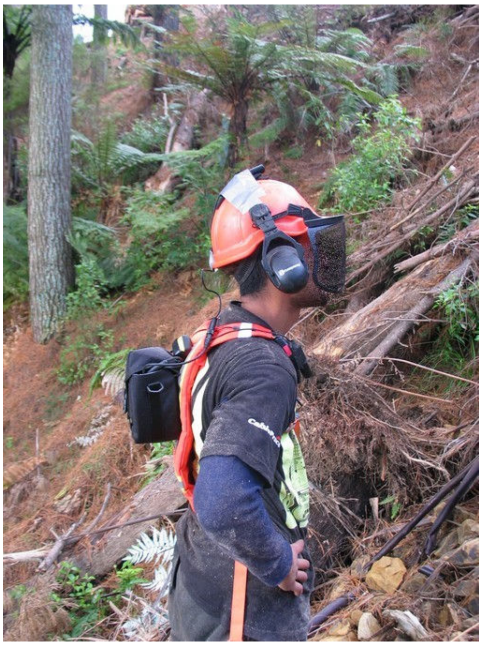

Figure 4. A working tree faller wearing audio and visual data capture hardware (Parker et al., 2009).

The software used to analyse some of the data collected in the field is shown in Figure 5.

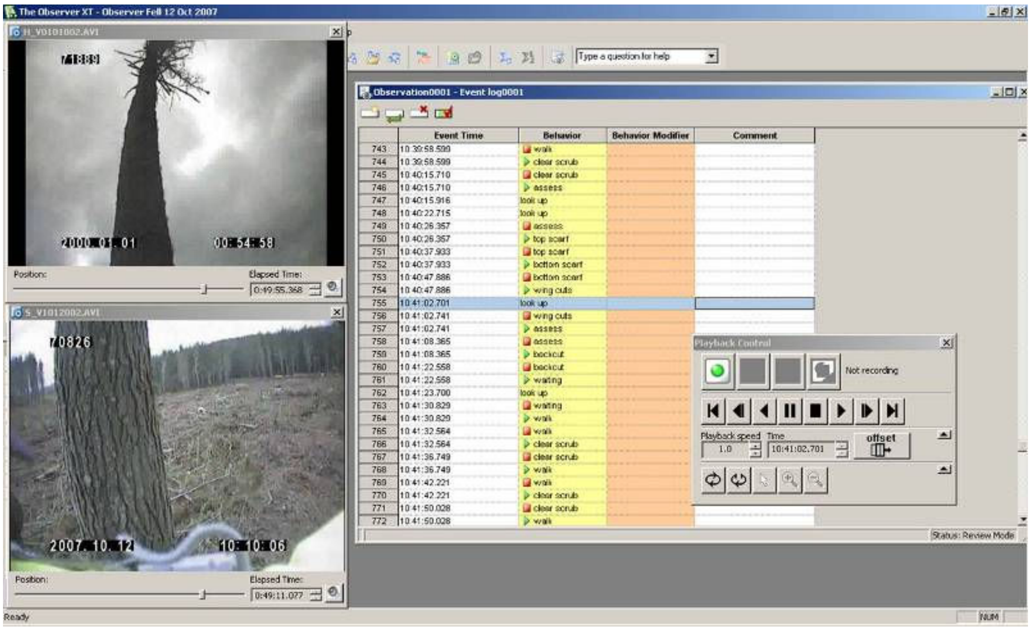

Figure 5. An example screenshot of the software used for field data analysis (Parker et al., 2009).

Literature data

An effective model should have more than one set of underlying productivity equations. The purpose is to mitigate bias that is intrinsic to productivity studies, which are by nature empirical studies conducted under unique conditions of site, stand, machines, operators and weather. Utilising multiple equations to define the elements/cycle/productivity for machines/systems mitigates some of the bias providing a more applicable output.

An extensive recent review of the literature showed that there has been very little research into harvesting on steep terrain either in New Zealand or around the world in recent years (Amishev et al., 2009). Literature on modelling different aspects of the harvesting system or the whole supply chain system, revealed a number of different approaches, although many of them were dated and related to different countries, species or logging systems that are not commonly used in New Zealand (e.g., selective logging, production thinning, etc). However a number of the concepts used, and the situations modelled, were found to be comparable with the New Zealand situation, and this information was used to cover areas of the model where there was not sufficient data to represent a relationship.

Data analysis

All data analyses were conducted in SAS (SAS, 2008). Analysis of Variance (ANOVA) was performed to test the difference between the means of harvesting systems, and multiple regression was performed to determine which of the parameters affected daily average production (PROC CORR). It is important to note that one cannot extrapolate outside the data space, i.e. beyond the range of observations as *jointly* defined by the data. With a limited dataset for this type of analysis, this constraint can be severely restricting. A stepwise regression was performed to investigate which independent variable played a significant role in predicting the average daily productivity (PROC REG). From these analyses, equations relating the various parameters to the average daily production and productivity were developed. These equations are required in the modelling process.

Model development

In 1980, a review of existing Tree to Mill Forest Harvesting Simulations models was undertaken and eight models were identified, each using a different approach to the complex problem (Goulet et al., 1979a). Since then a number of additional approaches have also been explored, including system dynamics models (McDonagh et al., 2001) and interactive simulation systems (Wang et al., 1998; Wang and Greene, 1999). In the interactive models, simulations are performed by moving machine images within stand maps on the computer screen. This allows the model to realise the implications of some operator decisions (e.g. which tree to select next when felling) however it may not take into account many of the real life impacts on productivity (e.g. machine breakdowns, operator day to day variation, skid blockages). One issue with a number of the models is the necessity to have detailed prior knowledge of the harvesting system being modelled in order to successfully simulate the relationship between harvest site attributes and system production (Baumgras et al., 1993).

A dynamic systems modelling approach was considered to be an ideal way to examine the numerous interrelated variables within a Harvesting System, and such an approach has been used in prior work internationally (McNeel and Rutherford, 1984; Baumgras et al., 1993). For this project, the first steps in model development required:

- identification of the relationships that can impact on productivity within the system; and
- mapping these using a causal loop diagram.

The Research Team developed a comprehensive causal loop diagram relating the factors that may influence cost of production in a New Zealand steep country harvesting system (Fig. 6). This diagram aimed to identify the parameters required to model the harvesting system. As with previous models, the chosen approach needed to recognise the fact that there are both factors impacting on productivity that are external to the crew (i.e. stand parameters) as well as those directly associated with the crew (e.g. machinery, crew numbers, type of processing etc).

Once the equations relating various factors to productivity had been determined using regression analysis (see Appendix 1 for details of the equations), the model was developed in Powersim Studio 8[1]. This programming platform allowed the advantages of graphical representation of the model, and the inclusion of causal loops, where the cause and effect can feed back on each other.

Once the model was developed, a sensitivity analysis of the system was performed to identify critical areas where operational, systems or human productivity interventions could lead to improved overall productivity.

PowerSim (www.powersim.com) is a systems dynamics modelling package. In the mid 1980s the Norwegian government sponsored research aimed at improving the quality of high school education using system dynamics models. This project resulted in the development of Mosaic, an object oriented system aimed primarily at the development of simulation based games for education. Powersim was later developed as a Windows-based environment for the development of system dynamics models that also enables packaging as interactive games or learning environments. Powersim's modelling and simulation tools are used to map formal mental models into models that can be simulated and analysed on computers.
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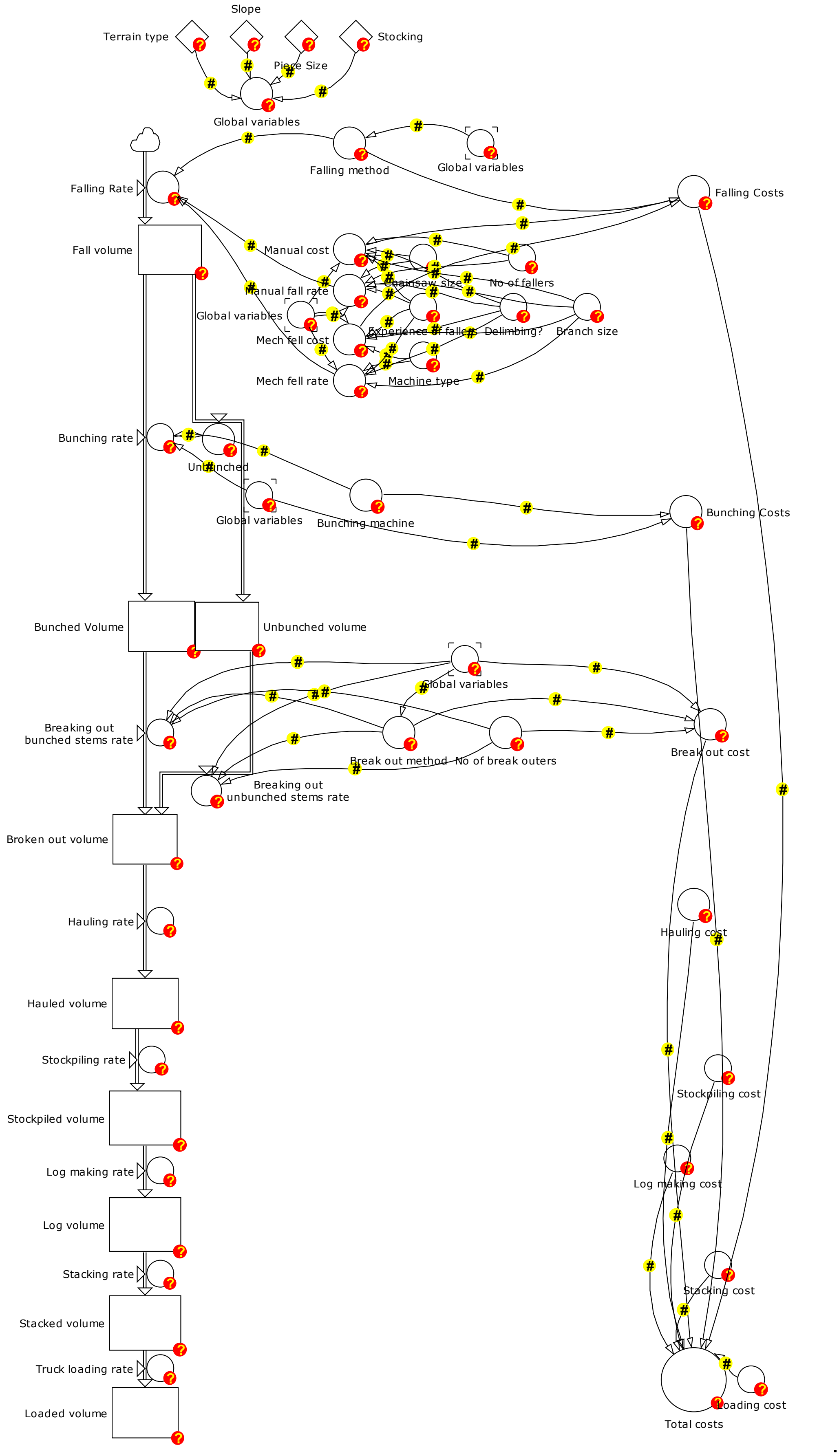

Figure 6. A full causal loop diagram examining a harvesting system on steep slopes.

Results and Discussion

Industry data collection issues

There were a number of common factors that impacted the quality of the data:

- Confidentiality was considered an issue by some companies, despite the fact that actual logging costs were not requested; all identifiers were removed from all data points (no crew names, company names, or actual harvest areas were used); and the data was kept confidential by researchers,
- Contracting staff appeared to lack time to collect the data. Companies agreed to provide at least four additional data sets which did not eventuate.
- Data received were often disparate and difficult to merge, given that different companies had different methods and drivers for collecting and retaining information.

Some companies felt that production, and the factors that impact on it, are strictly the domain of the logging contractor, provided the contractor maintains appropriate health and safety systems; operates within the environmental and regulatory constraints of the harvest area; and performs to the agreed production target. The production targets may be altered over time depending on the company's woodflow requirements, however this would result in a discussion with the contractor as to whether an altered target was achievable rather than a direct study on the crew's potential productivity. Such companies are unlikely to keep detailed records on crew composition, either in terms of machinery or staff numbers.

Other companies aim to work more closely with their contractors, identifying ways in which a contractor's combination of staff, skill base and machinery can work with infrastructure to operate more cost effectively. These companies may spend more time targeting crews to specific blocks and areas, and in some instances may keep records on machinery operated by different contractors. However it is more likely that this level of detail would be maintained through close communication with the contractor rather than keeping records on their capability, beyond very basic information such as hauler type and tower height that will assist with harvest planning.

To facilitate improvements in future studies of this kind, it is recommended that:

1. A standard list of variables is produced to indicate to companies and contractors the type of data that would be useful for studies of this kind should they wish to improve the quality of their data collection.
2. Standard definitions are produced for each variable with recommended measurement methods for quantitative variables or carefully described classifications for qualitative variables.
3. Improved methods are developed for quantifying variables influencing harvesting productivity (e.g. LiDAR to describe stand variables). While these methods may only be applicable for scientific studies, this approach may improve the usefulness of studies such as this one.

Industry data analysis for inclusion in the dynamic systems model

A range of attributes were received from the various companies (Table 1). All company data was combined yielding 57 observations and 12 variables (Table 1 plus "company" being another variable). Productivity was defined as estimated productivity as used for planning and rate setting purposes, as the actual production of a crew can vary markedly within a harvest area for a variety of reasons that may not necessarily reflect the productive capacity of the crew. The responses varied illustrating the different company approaches to the contracting workforce, and the level of involvement desired in appropriate rate setting. While this information was outside the scope of the project, it illustrated one of the problems with data gathering when different companies keep different types and levels of data. In addition, companies may keep little information on machinery or performance beyond those indicators that directly affect company performance (volume and grade recovery).

TABLE 1: Attributes Collected by Harvest Area

Attribute	Number of Data Points
Terrain Class	302
Ave Daily Prod	302
Piece Size	302
Hauler (Y/N)	57
Number of Machines	57
Number of Workers	57
Harvest Area Size	57
Stems per hectare	57
Volume per hectare (calc)	57
Mechanical Processing (Y/N)	57
Mechanised Felling (Y/N)	57

A database of information was compiled and this was analysed to study the relationships between the available attributes. The data were analysed as two separate sets, with terrain class, piece size and average daily production treated as one data set, and all other attributes, including average daily production treated as a second data set. A number of other attributes in addition to those listed were gathered however it was not possible to create a clean data set that linked these attributes to average daily productivity. Statistical analysis performed on the data gathered from companies showed only a very weak relationship between terrain class, piece size and average daily production (Fig. 7).

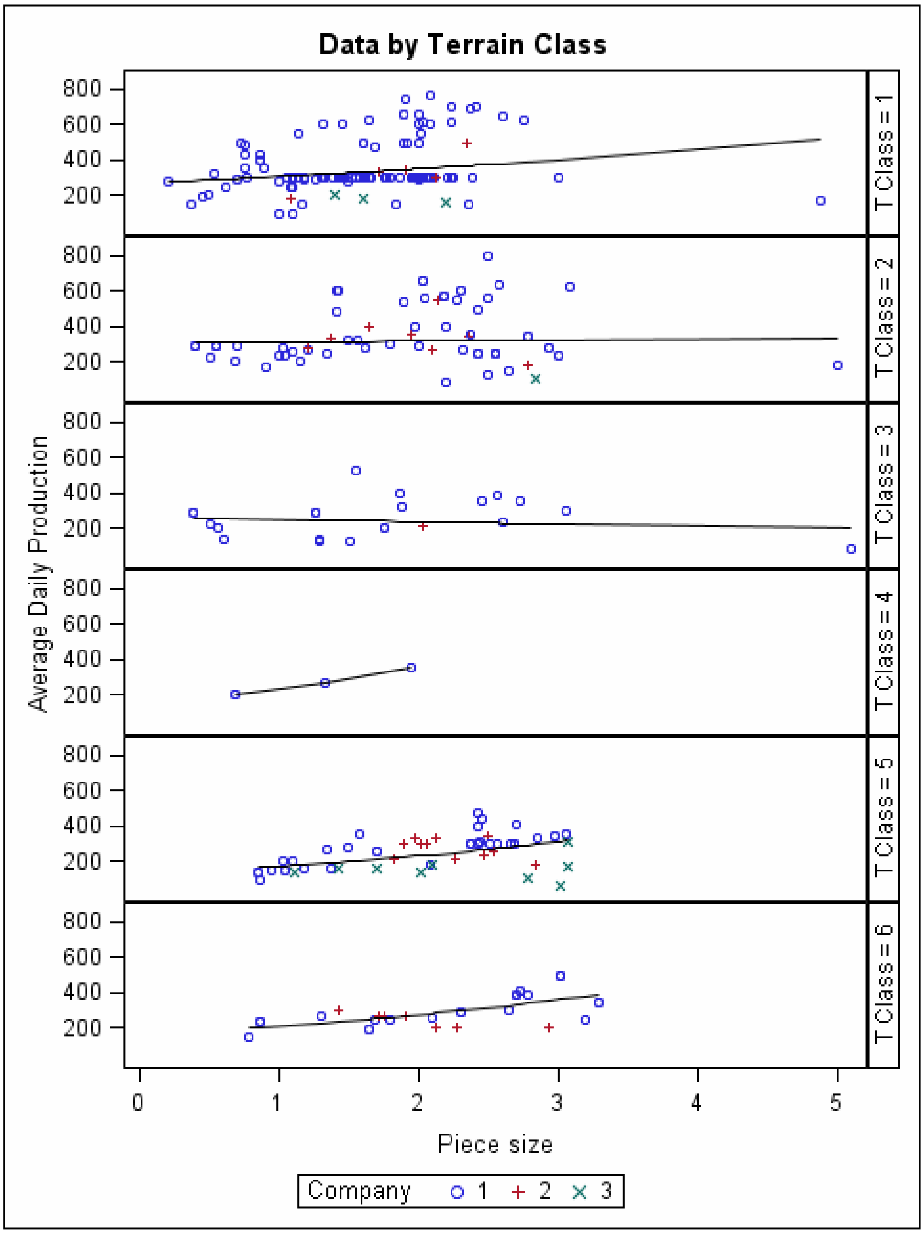

Figure 7. Predicted values (lines) of average daily productivity for each terrain class, with company data points.

A regression function predicting average daily productivity (ADP) from piece size was examined:

$$\mathbf{ADP = exp(\beta_0\ Terrain\ Class+(\beta_1 Terrain\ Class*Piece\ Size)}$$

Terrain class and company were included as categorical variables, together with all interactions. Residuals were examined. Heterogeneity of variance was found and a log transformation of the average daily productivity rate was made. Company had no effect on explaining the variability. The only significant source of variability was the piece size and terrain class interaction (p=0.0093). Consequently, the company was omitted from the model and the data refitted. Results are summarised in Table 2.

TABLE 2: Summary statistics from a regression function predicting average daily productivity

Source:		P values
Piece Size		0.0077
T_Class		0.0003
Piece Size* T_Class		0.0052
Model parameters:		**Estimate**
β_0	T_Class = 1	5.595
	T_Class = 2	5.736
	T_Class = 3	5.584
	T_Class = 4	4.980
	T_Class = 5	4.871
	T_Class = 6	5.088
β_1	T_Class = 1	0.135
	T_Class = 2	0.014
	T_Class = 3	-0.054
	T_Class = 4	0.463
	T_Class = 5	0.291
	T_Class = 6	0.266
Fit statistics:		
R^2		0.185
$S_{y.x}$ [1]		0.400
CV		7.03

Considering an estimate of the average daily productivity in Terrain Class 5 for a piece size of 2.04, the result would be:

$$ADP = \exp\left(4.871 + (0.291 * 2.04)\right) = 236.19 m^3 / day$$

The coefficient of correlation (R^2) shows that these variables, although statistically significant, explained only about one fifth of the variation in average daily productivity. Considering the nature of harvesting systems and the limited data set, this result is not surprising. In fact, a recent analysis of data from a New Zealand forest industry benchmarking data set, including 14 companies from around the country, concluded that productivity was not well correlated with average piece size, average slope or average extraction distance (Visser, 2009). It included both ground based and cable logging systems. In the absence of better data sets or regression models, the incorporation of these relationships into the model would ultimately determine its effectiveness.

A stepwise regression was performed to investigate which of the 10 independent variables played a significant role in predicting the average daily productivity. A scatter matrix of variables was produced and residuals were examined (Appendix 2). The stepwise regression showed that that the following variables were significant (Appendix 2):

- the use of the hauler;
- the number of workers;
- the size of harvest area; and the type of processing (mechanical or manual).

Stand stocking in terms of number of stems per hectare or volume per hectare was not found to be significant in terms of daily productivity. These findings coincided with the results from the nationwide benchmarking data set analysis (Visser, 2009) where productivity was found to be correlated with number of machines and workers, as well as harvest area size. Parameter estimates are summarised in Table 3.

TABLE 3: Summary statistics from a stepwise regression function predicting average daily productivity with multiple variables

Variable		Estimate	Standard error	F value	P value
Intercept		25.0092	59.43188	0.42	0.6756
Hauler	0	104.7300	28.0601	3.73	0.0005
Hauler	1	0.0000			
Number_of_Workers		20.0676	6.1342	3.27	0.0019
Harvest_Area_Size		0.6421	0.3291	1.95	0.0564
Processing	Manual	-56.9274	23.17872	-2.46	0.0174
	Mechanized	0.0000			

R^2 = 0.3765; Standard error of estimate =81.981; CV = 34.249.

A regression equation was developed using these parameters as a high level productivity estimator. As an example, considering a prediction of the average productivity (ADP) when a hauler is used, nine workers in the team, working in a harvest area of 100 ha, and mechanised processing the model would yield:

$$ADP = 25.0092 + 0 + (20.0676 * 9) + (0.6421 * 100) + 0 = 269.83 m^3 / day$$

The coefficient of correlation (R^2) indicates that these variables explain about 40% of the variation in average daily productivity. Again, considering the nature of harvesting systems and the limited data set, this result is not surprising. Other regression models, predicting ADP for ground-based harvesting systems report coefficients of correlation (R^2) of 0.67 up to 0.80 when additional variables such as average slope, number of log sorts, and location of log processing are included (Visser, 2009). Inclusion of such information (and thus the potential to improve the model) was beyond the scope of this project.

Three cable logging crews were studied as part of the collection of ***validation data***. In an effort to capture greater variability, they were chosen on the basis of the type of hauler they used (one of them used a grapple hauler, two were using chokers) and the piece size of the stand they were working in (ranging from 0.85 to 1.02 to 2.3 m^3). Findings are summarised in Table 4.

Table 4: Summarised parameters from field studies for validation data collection

Crew	1	2	3
SPH	497	437	242
Piece Size	0.85	1.02	2.3
Terrain	Short Steep	Short Steep	Short Steep
No of Workers	10	6	10
No of Machines	10	5	6
Hauler	Yes	Yes	Yes
Mechanised Falling	Some	No	No
Mechanised Processing	Yes	Yes	Yes
Average Haul Distance	163	253	128
Average Number of Pieces	2.98	2.2	2.21
Bunching	Some	Some	Some
Productivity (Bunching)	344	290	540
Productivity (No bunching)	231	235	392

Data from literature for inclusion in the systems model

Due to the poor fit of the industry data obtained, the suitability of relationships described in literature both from New Zealand and overseas was investigated for inclusion in the model. As previously stated, globally there has been very little research into harvesting on steep terrain, and almost nothing has been done on this topic in New Zealand for the past 10 years (Amishev et al., 2009). Relationships used for variables were selected based on their likely fit to the New Zealand conditions, either from their origin, the species, piece size or equipment used in the specific study. Where possible these relationships were then tested against available data to ascertain fit.

Diameter at Breast Height (DBH), used in falling calculations, was derived from piece size as all harvest area data supplied included an average (harvest area) piece size but no DBH information. This formula was then tested against actual tree measurements from Scion's Permanent Sample Plot (PSP) database, including regional data from Northland, Nelson, Bay of Plenty, Hawkes Bay, Wellington and Southland. With over 460 observations, the total variance was within 4% of measured DBH.

Walk distance for fallers was also calculated from stocking assuming a square planting pattern to give an average distance.

Machine productivity calculations were derived from a combination of identified studies (Kluender and Stokes, 1994; Anderson and Young, 1998; Gleason, 1984; Makkonen, 1989; McConchie and Evanson, 1995; Lortz et al., 1997a) and calculations based on individual machine capability. Data were collected on a large variety of machines including mechanised fallers (both feller bunchers (Hemphill, 1991) and falling heads (McConchie and Evanson, 1995), skidders (Adebayo et al., 2007; Lortz et al., 1997a)(wheeled – both cable and grapple), mechanised processing (Gleason, 1984; Spinelli et al., 2002; Skoupy et al., 2007), manual processing (Murphy, 1984; Robinson and Evanson, 1992), fleet / sort / stack (excavator (Murphy, 1984) and rubber tyred loader (Vaughan, 1989), crew transport and other associated crew costs (for example tail holds, hauler shift times, ropes, chainsaws etc).

Hauler Productivity calculations used from international sources were also analysed against available New Zealand data. These were tested against 32 data points for existing harvest area with estimated daily productivity, and came within -3.85% total variance (small hauler), 2.28% (large hauler) and 46.4% for the grapple / swing yarder calculation.

Based on the foregoing calculations and relationships, the prototype Harvesting System Productivity Model was developed (Fig. 8). There are three types of input parameters to the HSP Model:

- Site – terrain class, haul distance.
- Stand – piece size, stand stocking, harvest area size.
- System – pieces per drag/cycle, number of machines and workers, processing method, type of hauler, bunching options.

The model outputs include productivity measurement in cubic meters of wood produced per day (m^3/day) and cost per unit in NZ dollars per cubic meter of wood (\$/m^3) based on costs listed in Appendix 3.

The site and stand parameters represent terrain and tract characteristics which constrain productivity of harvesting systems. The model's user interface includes sliding scales to allow input of the key parameters – Terrain class, Piece Size, Haul distance, Stocking and Average pieces/drag. The user can also directly enter the actual figures for any of these parameters. Entry of the number of machines, type of machines and number of crew is via a table completed by the user. Hauler utilisation is entered as a set parameter and for model testing, the model was run at two utilisation levels, i.e., 80% based on North American studies and 73.75% based on New Zealand information.

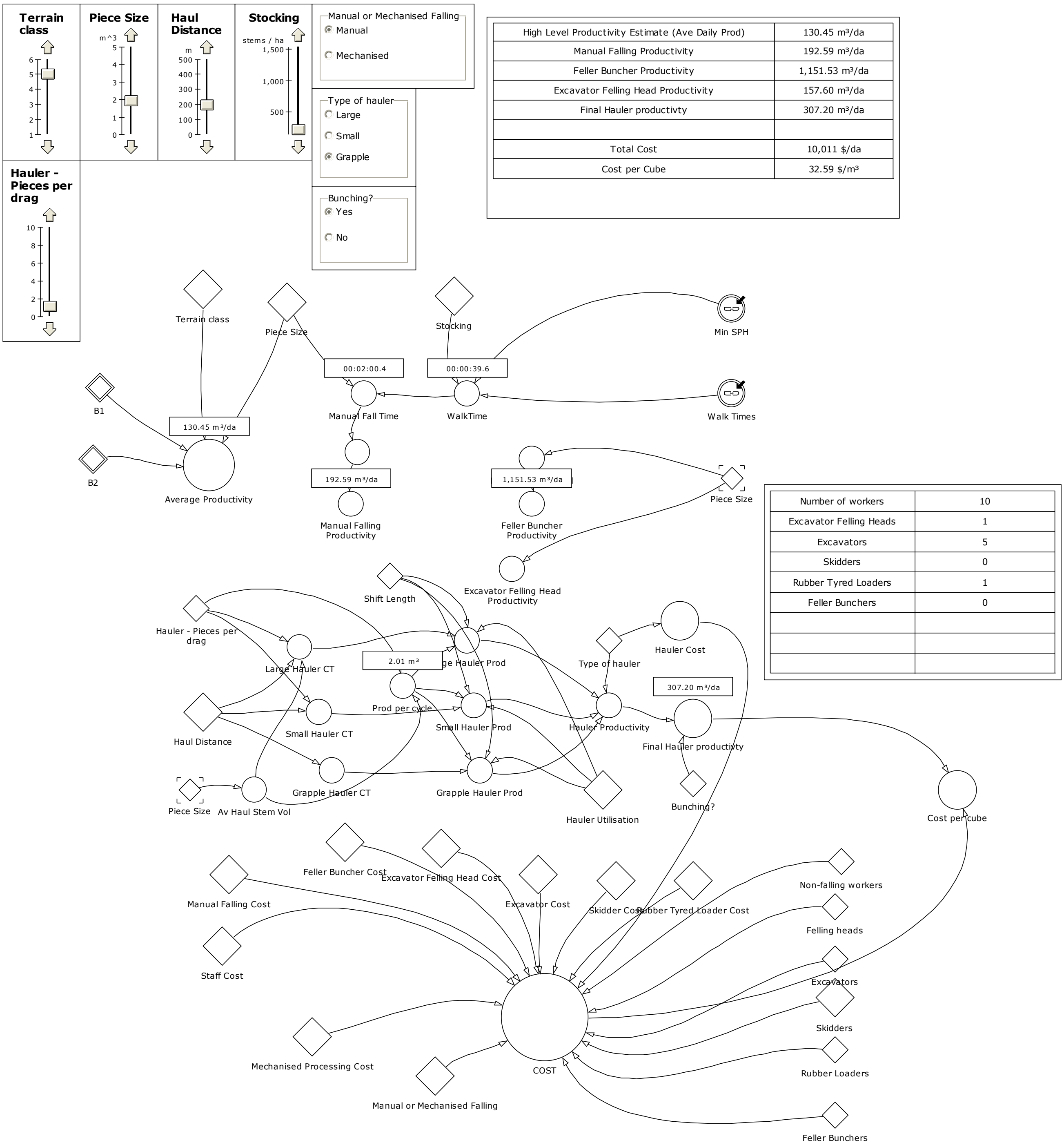

Figure 8. Harvesting system productivity model.

Model validation

Once the model was developed using the relationships derived from analyses of industry data, and from the literature, the validation dataset was used to test its accuracy. The productivity data from 3 crews is summarised in Tables 5 and 6. Using the information compiled, the model was used to estimate production for each crew both with and without the use of bunching (if the data were available). Productivity was calculated at two hauler utilisation levels – 80% (Table 5) and 74% (Table 6).

Table 5: Observed and Model estimated productivity for 3 hauler crews at assumed 80% hauler utilisation

Crew	Actual Prod	Choker Model	Grapple Model	Variance Choker	Variance Grapple
1 - Bunched	344	245	537	28.8%	-56.1%
1 - Unbunched	231	191	516	17.3%	-123.4%
2 - Bunched	290	189		34.8%	
2 – Unbunched	235	152		35.3%	
3 – Bunched	540	378		30.0%	
3 – Unbunched	392	364		7.1%	

Table 6: Observed and Model estimated productivity for 3 hauler crews at assumed 74% hauler utilisation

Crew	Actual Prod	Choker Model	Grapple Model	Variance Choker	Variance Grapple
1 - Bunched	344	233	469	32.3%	-36.3%
1 - Unbunched	231	181	451	21.6%	-95.2%
2 - Bunched	290	173		40.3%	
2 – Unbunched	235	150		36.2%	
3 – Bunched	540	357		33.9%	
3 – Unbunched	392	343		12.5%	

As can be seen from the tables, there is a range in variance at both levels of utilisation. Model estimated productivity was on average about 25% and 30% lower than actually measured in the three short-term productivity studies at 80% and 74% assumed hauler utilisations, respectively. The estimates of the use of a grapple were well overstated (more than 50% higher than actual) hence the formula used for this system does not appear to be representative based on this crew. These results suggest that more data is needed to strengthen the model and improve its effectiveness in productivity and cost estimations. The difficulty in obtaining crucial site, stand and system information from forest industry members, as well as the scarcity of developed relationships from the literature, are major contributors to the model's variance from actual values. Nonetheless, complex models combining site, stand and system information, while useful for sensitivity analyses, typically do not accurately predict either absolute productivity or absolute cost efficiency at the level of detail and accuracy ideally desired[7].

On the other hand, however, this prototype model is only a first attempt at modelling New Zealand specific forest cable harvesting systems and one of very few on an international scale. Hence, with increasing amounts of information and developing productivity relationships through ongoing research efforts in New Zealand (Parker et al., 2009; Marshall, 2008; Evanson, 2010) and internationally, this model will be constantly improved. It is currently modelling the cable harvesting system on a setting basis without including longer term factors such as moving between settings and between harvest units, system delays, landing storage delays, transportation, etc.

Sensitivity analysis

A sampling-based sensitivity analysis was performed, in which the model was executed repeatedly for combinations of values sampled from the distribution of the input factors. Once the sample was generated, a simple input-output scatter plot was used to derive sensitivity measures for the variables of interest daily productivity (m^3/day) and unit cost ($\$/m^3$). Several scatter plots were generated to investigate the effect that some of the factors (all others kept constant) would have on daily productivity and unit cost. Two of the most influential factors were determined to be the number of pieces per drag/cycle (Fig. 9) and haul distance (Fig. 10). Their effect on the final unit cost is proportional to that on daily productivity.

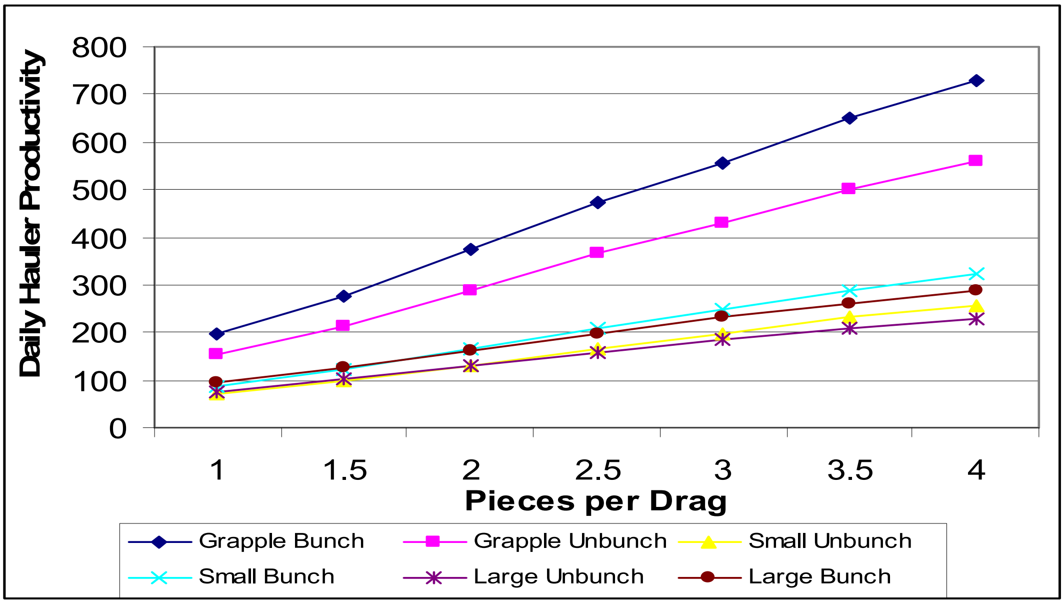

Figure 9. Scatter plot illustrating the effect of changing number of pieces per drag on daily hauler productivity.

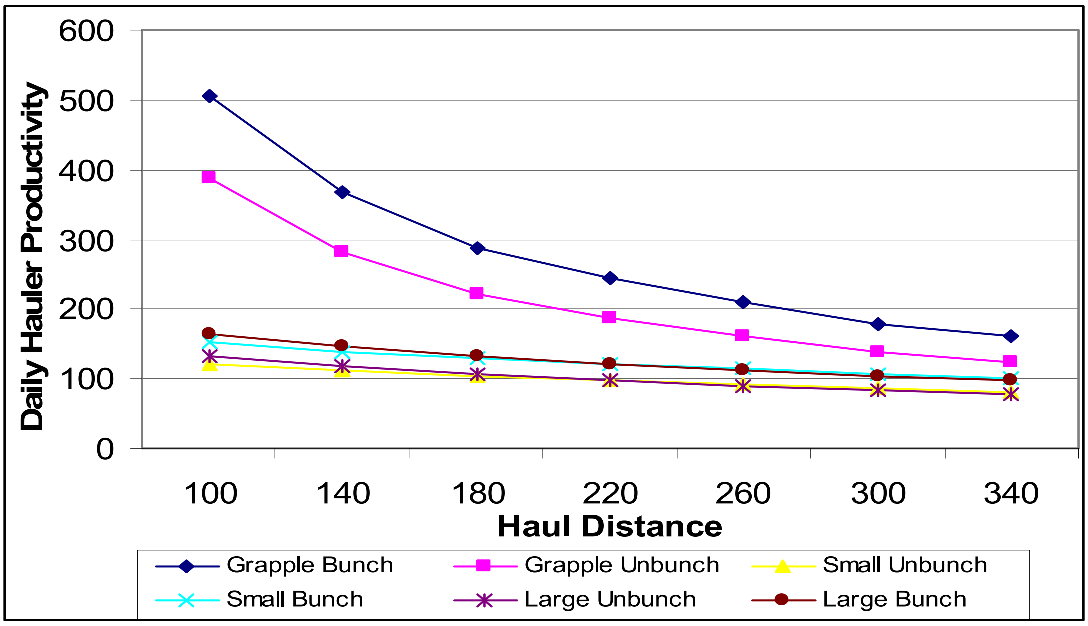

Figure 10. Scatter plot illustrating the effect of changing haul distance on daily hauler productivity.

Another obvious influential factor noted from these figures is the effect of bunching or accumulation of wood in one location for later extraction. Based on these results it is obvious that in order to improve productivity and hence reduce harvesting costs per unit of wood, efforts should focus in the following areas:

- Enable bunching of wood in various terrain, weather, and stand conditions – on steeper terrain that would require specialised purpose-built machinery or other means of enabling conventional machinery to work on steeper and more fragile slopes. Strong emphasis on human safety and ergonomic working conditions should comprise part of the efforts.
- Increase number of pieces per drag/cycle – this is partially addressed by bunching if the practice is employed. Another way of achieving that, especially with larger piece size is to enable a larger payload for the haulers by better cable deflection and using different cable systems allowing larger payloads over a given terrain. Better planning of hauler set-up locations and roadlines by using more detailed terrain models (LiDAR and GIS), and the incorporation of various types of carriages would all contribute greatly to achieving larger payloads.
- Match systems to stand conditions – grapple haulers are much more productive in shorter haul distances than those with chokers. Their advantage is greatly reduced over longer haul distances. Reducing the haul distance is not always the more efficient solution – while it would generally increase productivity, building of new roads and landings to facilitate that may actually increase the final unit cost. In more broken terrain and fragile soils, employing longspan and multispan skyline systems may prove more cost effective by savings from roading and land-clearing costs.

Concluding remarks

One study of Tree to Mill Forest Harvesting Simulation Models concluded that, of the eight models studied, although each model examined the same process (timber harvesting), no consensus exists on what constitutes the essential elements of a simulation model (Goulet et al., 1979a).They further state that empirical data, average values, regression, equations and parameters for theoretical probability distribution are possible ways of introducing machine operating characteristics. The requirements for obtaining such data may mean extensive field work doing time and motion studies.

Many of the models studied (Goulet et al., 1979a; Wang and Greene, 1999; Lortz et al., 1997b; Goulet et al., 1980 Goulet et al., 1979b; Mellgren, 1990) looked at ground based harvesting where the machine and skid site interactions are much more likely to impact on productivity, as will certain external factors such as terrain class. With cable extraction, it is most likely that the hauler is the productivity bottleneck within the harvesting system and therefore only those parameters that directly impact the hauler productivity are the critical elements that determine system output. For example, where the steepness of the terrain may have a major impact on productivity of a ground based operation this is less likely to be a determinant of a cable system. However average haul distance, piece size and machine utilisation (all having a direct impact on the productivity of the hauler) will have a direct influence.

The introduction of new technologies or practices in steep country systems that can directly affect hauler productivity will therefore be the only way to improve the systems productivity if this is the case. However, improvements in efficiencies in other areas could have a positive impact on cost of production through reducing total cost against a given production. An example of such a change is the practice of bunching for cable extraction which in the past has been difficult due to the restrictions of using available tracked machines on steep terrain. The challenges involved to include such practices in a systems model is the lack of available data (or existing applicable relationships modelled internationally) to develop a usable formula. Then, there is often a lack of local actual information to test the hypothesis of the model due to the cost of gathering such data.

The aim of the current study was to produce a prototype systems model that represents a trend in productivity and associated costs to allow comparison of different technologies and processes. While there is reasonable variability of modelled productivity compared to the actual observed in a validation field study, this is to be expected due to the high level of variation within any crew situation that can not be taken in to account. Studies have confirmed that differences in performance by crews with similar configurations in equivalent conditions in the order of 30% are not uncommon (Lortz et al., 1997b). This is within the tolerances of the prototype model.

Areas for further development in the model include the incorporation of further information that impacts on productivity as it becomes available. Work on the impacts of bunching is ongoing and this will be used to refresh the numbers currently being used, when there is sufficient information to update and test. Another area where research may soon be available is the impact of skid size on productivity, or the practice of using machinery to present logs to a grapple.

Detailed predictive models that aim to estimate daily production of a logging crew in a specific stand are unlikely to be directly utilised by industry as, to a large extent, they leave the contract work force to determine rates through competitive processes such as tendering. Therefore systems modelling is primarily useful in a research capacity for allowing comparative assessment of cost and productivity from the impacts of changes either to technology or process.

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Appendix 1 – Productivity functions used

Global Variables:
(No impact on cost)

Terrain Class (1-6)

Terrain Class	B_1	B_2	Description
1	5.595	0.135	0-10% dh, 0-5% up
2	5.736	0.014	10 – 20% dh, 5 – 10% up
3	5.585	-0.54	2 and 4
4	4.98	0.463	To 32% dh, to 15% up
5	4.871	0.291	Hauler < 400m
6	5.088	0.266	Hauler > 400m

Variable entered. Impact on productivity.
Where: AP=exp((B_1+(B_{2*} Piece Size)) for a given terrain class.
(Use where no crew info)
(Statistics from industry data/Colleen)

Haul Distance (Dist) (if available)
Variable entered. Average in metres
If not available select Terrain Class 5 (250 average) or 6 (350 average).

Piece Size (PS)
Variable entered. Piece size used is merchantable piece size (m3).

Average Haul Stem Volume (SV)
=1.132*PS-0.124*PS^2
(Functions to Predict Average Piece Size and Average Haul volume for NZ Clearfell Cable Logging Operations – G Murphy)

Stocking (SPH)
Variable entered. Number of stems per hectare.

Spacing
Distance between trees (m). This was assumed to be a square spacing and is calculated by the formula "Square Root (10000/stocking)".
(calculated spacing)

Production Variables
(Impact on Production and Cost)

Falling Rate
Falling can be manual or mechanised (select applicable).
Manual Falling:
Productivity/Faller

Fall Time (FT)
=(0.0346*((PS/0.0021)^(1/1.7907))-0.223+walk time)
(Tony E – derived from NZFS manual)

Fall Time plus Fuel/Access (FTFA)
=FT+(FT*0.035)+(FT*.02)
(Tony E – derived from NZFS manual)

Walk Time

SPH		
Min	Max	Walk Time (mins)
137	160	0.76
161	185	0.715
186	210	0.68
211	234	0.66
235	278	0.62
279	340	0.575
341	401	0.53
402	463	0.495
464	556	0.46
557	679	0.41
680	803	0.38
804	926	0.36
927	1050	0.335
1051	1174	0.305
1175	1297	0.295
1298	1421	0.285
1422	1544	0.27

(Tony E – derived from NZFS manual)

Productivity/Faller
Assuming an 7 hour working day, utilisation of 90% and delays of 7.3% of FT
(Harvesting Second Growth Coastal Forests: Summary of Harvesting Performance)
Prod = (420*0.9)/(FTFA*0.927)
(Calculated)

Mechanised Falling:
Productivity/Machine
Feller Buncher
Productivity/(m3/PMH) = 118.80+252.96*log(PS)
(Harvesting Second Growth Coastal Forests: Summary of Harvesting Performance)
Based on a large machine and includes minor delays

Daily rate = prod * 8* .75
(8 hour day with 75% utilisation)

Excavator/Felling Head
Productivity/(m3/PMH) = 81*piece size

Hauler
No. of Peices
Average number of pieces per drag – entered variable (discrete number)
Small Hauler
Cycle Time (CT) = Out/InHaul Time (OIHT) + Hook Time (HT)+ Unhook Time (UT) + FT
OIHT =0.310+0.0106*Dist
HT = 1.593+1.240*log(no. of pieces)
UT = 0.326+0.107*(number of pieces)
FT = 0.021
Delay (Del) = 4.2*CT

Prod/cycle (PC) (m3/min) = SV*number of pieces

Shift Length (SL) mins = 8.0 *0.8*60 (at 80% utilisation)
Prod/day = (SL/(CT+Del))* PC

Large Hauler (default if size unknown)
No. of Pieces
Average number of pieces per drag – entered variable (discrete number)
Cycle Time (CT) = Out/InHaul Time (OIHT) + FT
OIHT =0.20+0.00818*Dist+0.0293*(SV* number of pieces)
FT = 2.93
Delay (Del) = 4.7*CT

Prod/cycle (PC) (m3/min) = SV*number of peices

Shift Length (SL) mins = 8.0 *0.8*60 (at 80% utilisation)
Prod/day = (SL/(CT+Del))* PC

Grapple
Cycle Time (CT) = Out/InHaul Time (OIHT) + Load Time (LT) + FT
OIHT =0.048+0.0080*Dist
LT = 0.038+0.0031*Dist
FT = 0.069
Delay (Del) = 3.9*CT

Prod/cycle (PC) (m3/min) = SV*number of pieces

Shift Length (SL) mins = 8.0 *0.8*60 (at 80% utilisation)
Prod/day = (SL/(CT+Del))* PC

Bunching
Impact on Prod
=Prod+ (prod*.8*0.25) (for a large or small hauler with chokers)
=Prod+ (prod*.8*0.30) (for a grapple hauler)

Appendix 2 – Statistical analyses

Figure A2-1. Scatter matrix of variables used in the investigation.

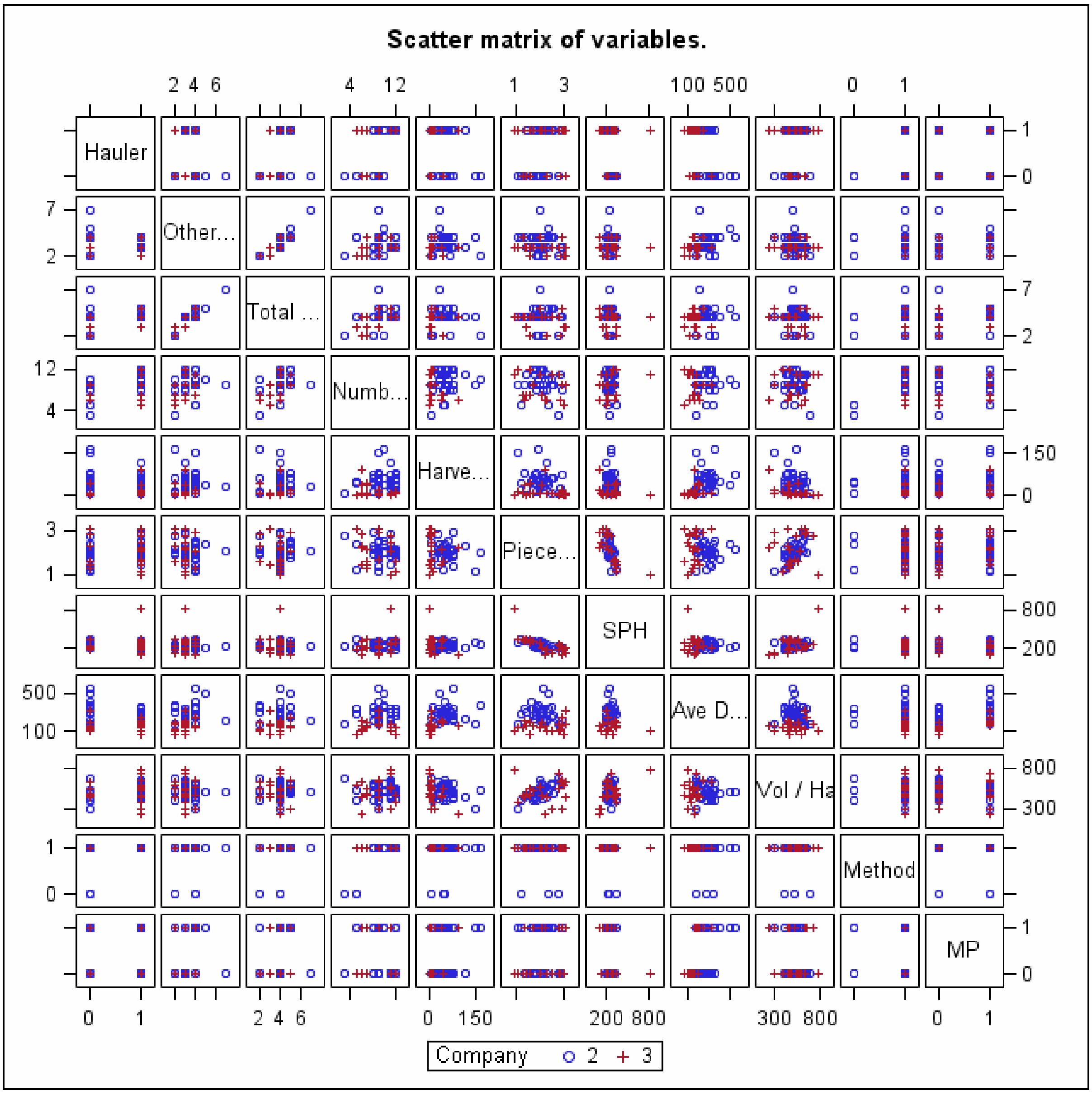

TABLE A2-1:Pearson matrix showing relationships between parameters, Pearson correlation coefficients (n=57) and values of significance (P-values)

	Hauler	Other Machines	Machines	Number of Workers	Harvest Area Size	Piece Size	SPH	Ave Daily Prod	Vol/Ha	Method	Processing
Hauler	1.00000	-0.10049 0.4570	0.40832 0.0016	0.51486 <.0001	-0.12962 0.3365	0.17388 0.1958	-0.03393 0.8022	-0.29182 **0.0276**	0.09501 0.4820	0.33333 0.0113	0.02500 0.8535
Other Machines	-0.10049 0.4570	1.00000	0.86718 <.0001	0.18340 0.1721	0.07288 0.5900	-0.15246 0.2576	0.02001 0.8826	0.28944 0.2237	-0.11602 0.3901	-0.02393 0.8598	0.28066 0.0345
Machines	0.40832 0.0016	0.86718 <.0001	1.00000	0.42597 0.0010	0.00199 0.9883	-0.05284 0.6962	0.00137 0.9919	0.11950 0.3760	-0.05889 0.6634	0.14489 0.2822	0.27002 0.0422
Number of Workers	0.51486 <.0001	0.18340 0.1721	0.42597 0.0010	1.00000	0.11172 0.4080	-0.14756 0.2734	0.14199 0.2921	0.16369 **0.0290**	0.04479 0.7408	0.52617 <.0001	-0.17256 0.1993
Harvest Area Size	-0.12962 0.3365	0.07288 0.5900	0.00199 0.9883	0.11172 0.4080	1.00000	-0.22889 0.0868	-0.09893 0.4641	0.39657 **0.0023**	-0.28755 0.0301	0.05247 0.6983	0.19172 0.1531
Piece Size	0.17388 0.1958	-0.15246 0.2576	-0.05284 0.6962	-0.14756 0.2734	-0.22889 0.0868	1.00000	-0.65017 <.0001	-0.06340 0.6394	0.29102 0.0281	-0.01202 0.9293	0.21395 0.1100
SPH	-0.03393 0.8022	0.02001 0.8826	0.00137 0.9919	0.14199 0.2921	-0.09893 0.4641	-0.65017 <.0001	1.00000	-0.08468 0.5311	0.42632 0.0009	-0.01765 0.8963	-0.18981 0.1573
Ave Daily Prod	-0.29182 0.0276	0.28944 0.0290	0.11950 0.3760	0.16369 0.2237	0.39657 0.0023	-0.06340 0.6394	-0.08468 0.5311	1.00000	0.01055 0.9379	-0.06489 0.6315	0.23953 0.0727
Vol / Ha	0.09501 0.4820	-0.11602 0.3901	-0.05889 0.6634	0.04479 0.7408	-0.28755 0.0301	0.29102 0.0281	0.42632 0.0009	0.01055 0.9379	1.00000	-0.05749 0.6710	-0.01089 0.9359
Method (felling or chainsaw)	0.33333 0.0113	-0.02393 0.8598	0.14489 0.2822	0.52617 <.0001	0.05247 0.6983	-0.01202 0.9293	-0.01765 0.8963	-0.06489 0.6315	-0.05749 0.6710	1.00000	-0.10833 0.4225
Mechanical or manual processing	0.02500 0.8535	0.28066 0.0345	0.27002 0.0422	-0.17256 0.1993	0.19172 0.1531	0.21395 0.1100	-0.18981 0.1573	0.23953 **0.0727**	-0.01089 0.9359	-0.10833 0.4225	1.00000

Appendix 3 – Cost estimates used

Manual Faller
Cost/Faller
Average cost/person based on 2009 LIRO Costing Model, 9 staff including one foreman
$250/pp/day

Mechanised Faller
Feller Buncher
Cost: $1285/day

Felling Head
Cost: $1285/day

Excavator
Cost: $815/day

Skidder
Cost: $795/day

Rubber Tyred Loader
Cost: $600/day

Staff
Cost: $250/day (average incl foreman)

Hauler Tower
Cost: $1,100/day

Hauler Yarder
Cost: $1,575/day

Mechanised Processing
Excavator/Processing Head
Cost: $1375/day

Bunching
Cost: $815/day