Waterford Institute *of* Technology

An evaluation of wood fuel production parameters from Irish Sitka spruce first thinnings

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Declaration:

No element of the work described in this dissertation has been previously submitted for a degree at this or any other institution. The work in this dissertation has been performed entirely by the author.

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Abstract

A comprehensive study of a number of in-forest wood energy supply chains was undertaken to collect empirical data on many aspects of both the stand and operational parameters therein. The data was then used to develop statistical models, so that a number of harvesting systems could be compared in a simulated environment. The simulated environment had two factors: the mean diameter at breast height (dbh) of the stand (cm), and the mean extraction distance (m). The harvesting systems compared were: cut to length (CTL) harvesting, CTL harvesting with chipping of the pulp assortment, and whole tree harvesting with terrain chipping of the whole trees. Not only were models developed on the productivity of the machines, but a taper equation, dbh to total height model, and a set of dbh distribution models were developed to predict the volumes of the assortments attributable to each harvesting system down to the tree level. The productivity models then used this data to estimate a cost of production per hectare for the harvesting systems. A value per unit volume of the assortments was taken from literature, and a profit analysis performed for each harvesting system. The simulation results show that whole tree harvesting and terrain chipping returns the highest positive profit for all levels of mean dbh at short extraction distances, but suffered from the machine interaction in the terrain chipping system at long extraction distances. The machine interaction between the terrain chipper and the chips forwarder was analysed using discrete event simulations. CTL harvesting and chipping of the pulp assortment returned the highest positive profit at longer extraction distances.

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Chapter 1: Introduction

1.1 General Introduction

Ireland has an emerging forest estate. It is estimated that only 1.5% of Ireland was covered by forest in the early 1900s. This low density was attributed to historical population increases demanding more agricultural land for food rather than forestry (Forest Service, 2008). The most up-to-date inventory of the Irish forest estate estimates that forest cover is now approximately 10% of the country, 625750 hectares, comprising of:

- 57% state owned forest
- 30% private grant aided forest
- 13% private non grant aided

(Twomey et al., 2007a)

The 30% private grant aided forest is a response to a grant initiative that was introduced 1981 to encourage private landowners to plant their land. Before this, the vast majority of the forest estate was publically owned. The grant scheme aimed to encourage farmers to enter the forest sector to improve their farm incomes (Forest Service, 2008). So much so, that Irelands national forest inventory (Twomey et al., 2007a) predicts that private ownership “should make up the majority of the national estate within one decade, if the afforestation programme continues”. Sitka spruce was the species that had already been adopted as the main commercial crop by the public forest sector, and this too was the most planted species by private landowners. As the planting initiative has only been in place for the past 31 years, a large proportion of the forest estate now comprises of young Sitka spruce plantations. The national forest inventory (NFI) estimates that (including both private and public ownership) the age structure at present is as per table 1.1.

Table 1.1: Age structure of Sitka spruce forest cover in Ireland (private and public owned)

Age class	1000 ha	%
1-10	112.14	34.2
11-20	120.9	36.9
21-30	38.68	11.8
31-40	40.93	12.5
41-50	14.15	4.3
51+	1.02	0.3
Total	327.82	100.00

(Twomey et al., 2007a)

The age structure shows that 71% of the Sitka spruce in the country is less than 20 years of age, and that this represents 37% of the total forest estate.

Therefore, there is a large proportion of the forest estate that is either at 1st thinning age, or nearing 1st thinning age. Thinning will add value to the final crop by allowing the stand to develop fewer, but better quality and larger stems at clearfell age, without reducing overall timber production (Hibberd, 1991). The 1st thinning operation is a silvicultural management tool, and the long term benefits can outweigh the costs. Russell and Mortimer (2005) used discounted revenue to evaluate the benefits of thinning at a net present value. They describe how for yield class 22 Sitka spruce, the landowner can actually spend €2170 per hectare first thinning a plantation without losing any overall investment. This shows how powerful thinning can be in adding value to the crop. However, the return on this investment will only be recoupable at the end of the rotation. As tree size is small at first thinning age, the costs may be greater than the immediate revenue from timber sales. For private landowners, who have received planting grants for the establishment of their forests, an immediate negative cash flow may prevent 1st thinning operations from taking place, that is, until tree sizes are large enough for a positive cash flow.

There will be an increased demand for forest based biomass over the next few years. The demand will come from Ireland's requirements to meet the European Parliament Directive 2009/28/EC by the year 2020. This directive targets Ireland with a 16% use of renewable energy by 2020 (European Commission, 2009). The COFORD roundwood demand group estimates that this will put a demand of forest based biomass at 3,084,000 m^3 in 2020 (the group assumed an energy value for wood of 6.9 GJ / m^3) (COFORD Roundwood Demand Group, 2011).

Phillips (2011) published a roundwood production forecast for Ireland until 2028. The forecast also included predictions on the volume of wood fibre that will be available for the energy market. Interestingly, this biomass for energy forecast also includes the stem volume from 7 cm to the tip, which has traditionally been non merchantable. The harvesting of this material would require a new integrated harvesting method which is currently not employed in Ireland. The forecast predicts that (including sawmill residues, and post consumer recycled wood) 1,453,000 m^3 will available for the bioenergy market in 2020 (Phillips, 2011).

This is an unprecedented condition for the forest sector in Ireland. A new resource is emerging in the form of the young grant aided private plantations established over the past 30 years. Silviculturally, these plantations need to be thinned. By 2020, the demand for wood energy will be far above supply. The forecasts of the available volume also assume that the thinning of all the plantations that are due to be thinned will occur on time. This will require planning and the development of wood supply chains, in particular, supply chains with integrated energy products. If ever, now is an opportunity to introduce new methods of harvesting small diameter trees for wood energy to support the silvicultural needs of the new forest resource, and to supply this biomass demand. However, as much of this resource is in the private sector, a positive cash flow will be needed from the operation for private landowners to engage in this silvicultural operation. The estimates of supply published by Phillips (2011) only uses wood fibre from existing roundwood harvesting and sawmill residues. However, with whole tree harvesting there is the possibility to recover more biomass than is forecast.

The research question investigated in this dissertation is

Under what conditions, if any, is a whole tree harvesting and terrain chipping system more favorable than a cut to length (CTL) system, from a profit perspective, as a method for first thinning Sitka spruce plantations in Ireland?

This will be accomplished by evaluating parameters affecting three methods of first thinning:

- CTL harvesting for sale of all roundwood products
- CTL harvesting for sale of sawlog and pallet products, and chipping of pulp products for sale to the energy market
- Whole tree harvesting and terrain chipping of whole trees for sale to the energy market

Importantly, the study will evaluate the immediate cash flow of operations and attempt to describe the conditions under which the value of the products produced will cover costs. A cost only analysis is not appropriate for comparing the harvesting systems, as the products produced are inherently different, and the volumes that can be produced. A cost only analysis may only prove that the system which does less, costs less. For example: If two harvesting systems (A and B) are compared where system A has a cost of €30 / m^3 and system B has a cost of €35 / m^3, system A may be assumed the more favorable. However, if system B recovers 50% more volume per hectare, the value recovered is much higher. But also, if products produced by system A have a much higher value per m^3 than system B, system A may still be more favorable.

This dissertation was written using the empirical data collected during the Forest Energy 2007-2008 programme. The forest energy programme was managed by Tom Kent of Waterford Institute of Technology, and Pieter D. Kofman of the Danish Forestry Extension. The objective of the forest energy programme was to characterise the production of woodchip as an alternative use for the low value material from Irish Sitka spruce first thinnings. Fundamentally, the driver behind the programme was the dissemination of information for the stimulation of a new market for first thinnings (including demonstration days of harvesting equipment), and thus encouraging good forest practice. The programme findings have been published by COFORD as *Cost-effective woodfuel supply chains in Irish forestry* (Kent et al., 2011). The programme was preceded by the Forest Energy 2006 programme, also managed by Tom Kent of Waterford Institute of Technology, and Pieter D. Kofman of the Danish Forestry Extension. These two research projects are the first comprehensive studies of wood energy supply chains in Ireland. Included in projects were studies of a Danish whole tree chipping system which had never before been used in Ireland. Therefore, this dissertation is the state of the art knowledge of wood energy supply chain systems in Ireland.

During the Forest Energy 2007-2008 program, a number of different harvesting systems were trialled on five sites in Ireland, and data was collected on their performance. The empirical data was in part collected by the author, along with collegeus as part of a research team. The aim of the presented dissertation is to add value to the data by making direct comparisons between the harvesting systems trialled. A huge amount of data was collected during the study, but, unfortunately, little statistical design was applied in the trials, not all systems were trialled on every site, nuisance factors were not measured which could impact on the systems, and fundamentally, the harvesting systems did not perform the same silvicultural operation.

The Forest Energy programme data can therefore be regarded as a number of separate case studies, with results that cannot be directly comparable to each other. The author of this dissertation overcame this problem by modularising the harvesting systems into their separate elements. By analysing the elements separately, models could be developed to describe each element. The harvesting systems could then be compared in a simulated environment. Therefore, what follows is an ad-hoc modelling solution to an experimental design problem. All analysis and modelling of the data was completed solely by the author.

To accomplish the cash flow analysis, not only do productivity models of the machines used in the harvesting systems need to be developed, but also a set of models to predict the harvestable volume. These volume models also need to be able to describe the multiple assortments attributable to each harvesting method, and the volume produced. The productivity models can then be developed to use harvested volume parameters as their inputs, and thereby associate the costs, and the revenue, appropriately. This evaluates the harvesting operation on a per hectare basis, meaning that the driving factor behind the operation is not the volume produced, it is the silvicultural thinning. Trees which have a very low, or no merchantable volume, still have to be removed from the forest, and this has a cost. The study models operations at the tree level to account for this.

There are two factors for the condition of the simulated environment:

- Tree size (characterised by mean dbh: 10cm to 20cm)

- Extraction distance (mean extraction distance: 100m to 1000m)

The dissertation is divided into 9 main chapters, including this introduction and a conclusion chapter. An overview of the chapters now follows:

- Chapter 2:

  A taper equation and a dbh to total height equation are developed for Sitka spruce first thinning trees. The models have the ability to predict the roundwood volumes of any specified assortments of a tree once the dbh of the tree is known. Along with their use in this dissertation, the models are also very relevant to pre-sales measurement for first thinnings in Ireland, and potentially have an application as a utility for forest managers over the coming years. This chapter accepted for publication in the journal *Irish Forestry*.

- Chapter 3:

  In this dissertation, the simulation environment will require dbh distributions to use with the taper and dbh to total height models. The dbh distributions of stands as described by the British Forestry Commission describe the main crop before thinning. The distributions are described by the mean dbh and a set of Weibull functions. In this chapter, transition functions were developed to change the before thinning dbh distribution into a thinning distribution (trees removed) that is representative of the thinning experienced in the harvesting trials. The distributions were then used with the taper model and dbh to total height model to describe the volumes harvestable from the thinning methods.

- Chapter 4:

  The cut to length harvesting and forwarding operations are analysed. A machine rate cost for the harvester and forwarder is calculated. Two models are developed. The first is a model that predicts the cycle time of the harvester from the harvested volume of the tree. The second is a model that predicts the cycle time of the forwarder from the mean extraction distance, the mean log size, and the load size. Both these models are then used with the data developed in chapters 2 and 3 to estimate the machine productivities under the simulation environment conditions.

- Chapter 5:

  The chipping of cut to length logs at the forest roadside is analysed .Two chippers are studied. A machine rate cost is calculated for each machine. A model for each chipper is developed that uses mean log size to predict the productivity (m^3/hour) of the chippers. These models are then used with the data developed in chapters 2 and 3 to estimate the machine productivities under the simulation environment conditions.

- Chapter 6:

  Whole tree harvesting using both motor manual and feller-buncher machines is analysed, and a machine rate cost calculated. A terrain chipper and chips forwarder are also analysed, a machine rate cost calculated, and models developed for to describe their productivity. The terrain chipper model predicts the cycle time of the machine from the mean tree volume being chipped in a load. The chips forwarder model predicts its cycle time from the average extraction distance.

- Chapter 7:

  A discrete event model is developed to evaluate the terrain chipping system productivity in the simulation environment.

- Chapter 8:

  Monetary values are assigned to the assortments produced by each thinning system. The values are based on prices as reported by Teagasc and SEAI. A cash flow analysis is presented by using the data from the previous chapters.

- Chapter 9:

  This chapter restates the results found in the study, identifies some practical implications of the information, and makes recommendations for future research.

1.2 Literature Review

The majority of the work in this dissertation is drawn from the following four topical areas: modelling and simulation, machine rate calculation, machine productivity evaluation, wood product characterisation.

1.2.1 Modelling and simulation

A model is an abstract representation of a real world system. Importantly, this representation must be a simplification of the real system. If a model were to be as complex as the system, it would actually have to be the real world system, and so for a model to be useful, a trade off must be made between the complexity of a model, and its accuracy. The function of a model is to describe the change of a system state due to changes in parameters of the system. The model should be simple to use, but realistic in its approximation of the real system (Anu, 1997). Models can take on a number of forms, from conceptual models to mathematical models (Botkin, 1993). In quantitative scientific research, particularly when simulation is required, models are usually mathematical statistical models (Beckert et al., 2001). Statistical models describe the relationship of variables using mathematic functions (McCullagh, 2002).

A simulation is the operation of a model to represent the operation of the real world system. Basically, it is the running of a model to evaluate its outputs for a set of inputs. The input values to a model in a simulation are user defined, but must be restricted to approximations of the real world system in order to avoid a *rubbish in: rubbish* out scenario. This is where the inputs are set to a combination of values which would not be experienced in the real world, and therefore the model cannot approximate a meaningful output. This restriction also goes further; models are developed using empirical data, but the data collected may not encompass all input values which can exist in the real system. Therefore, limitations must be defined as to the range of input values which can be used (Anu, 1997).

Simulation can be classified into two main groups: deterministic and stochastic. The difference between these two groups is that stochastic models use an element of randomness, whereas deterministic models do not. This means that for a set of input variable values, a deterministic model will always return the same output values, whereas a stochastic model will return different output values each time the model is run. The random elements of a stochastic model follow probability distributions that reflect their occurrence in the real world (Pidd, 1989). The identification and application of these distributions is a discipline in itself. Luckily there are software programmes that can be used to fit distributions to data, such as Statfit and Minitab. Each time a stochastic model is run, values are generated randomly from their probability distributions to use in the functions of the model. The benefit of this is that if the model is run a large number of times, a data set of possible outcomes is generated which can be analysed, giving a better approximation of the real world system. This is known as Monte Carlo simulation (Hamby, 1994). Computer software programmes are used to automate the repeated iterations to speed up the process. In this manner, a stochastic model is not solved like a deterministic model, it is run many times to create a history of the system and how it operates (Pidd, 1989).

When the system being modelled is complex, in the sense that the system comprises of a number of individual elements, the independence or interdependence of the elements dictate how the system should be modelled. In the case where the elements in the system are independent, the elements can be statistically modelled separately, and the results used together in a functional form (Murphy et al., 2010). For instance, a harvester and a forwarder operate independently in a

CTL harvesting system. If a model was required to estimate the cost of production for this system, a separate model for each machine could be used to asses their productivity. Using a deterministic model for each machine would be suitable. An hourly cost of each machine could be applied to the results to estimate the cost per cubic metre for each machine. The total cost per cubic metre for the CTL systems could then be estimated simply from the sum of the costs of each machine (Whiteman, 1999). In the case where the elements in the system are interdependent, the modelling may require a dynamic approach. This may be the case in a more complex system, such as a hot deck extraction and processing of timber at the forest roadside, where machines directly interact with each other. Dynamic modelling is when the model projects over time. In this case, stochastic models can be run that are controlled by logical arguments linked to a dynamic (time) element. This is known as discrete event modelling (Banks and Carson, 1984).

Mendoza and Vanclay (2008) describe how models used in forestry can be categorised into four main areas: "forest management planning and decision making, forest dynamics and growth projection, forest landscape and spatial models and participatory forest management models". This dissertation fits into the category of forest management planning and decision making, in particular, volume estimation and harvesting operations.

Models can be built for general industry decision support, or may be specifically built for research analysis. For example, the South African Harvesting and Transport Cost Model (Hogg et al., 2008) is a deterministic model for general industry use. The model predicts the total harvesting and transport costs of logging operations from user defined inputs. The model is written in JAVA computer language, and has a step by step user interface. The model uses standard machine rate costing techniques to calculate cost per productive machine hour, and all cost inputs (such as purchase price, fuel cost, etc.) are user defined. Whereas a discrete event model was developed by Talbot and Suadicani (2005) to analyse in-forest chipping and extraction systems. This model was written in the SAS statistical package, and was used to experiment with the systems through simulation. A research paper was published detailing the performance of the systems under different conditions.

Other models have been produced, such as the cost model for forest machine operation in wood cutting and extraction by Lan (2001). This model is a deterministic model based on standard machine rate costing techniques and productivity studies. The model has a user interface programmed for Microsoft Windows. Finke (1984) details the SPRINT model, a model that was used at over half a dozen Weyerhaeuser pulp mills at time of publication. The model was a stochastic Monte Carlo simulation model that was used as a management tool to predict the level of wood chip inventory. As suggested by Finke (1984), the ability of the model to give a distribution of outputs rather than a point estimate meant that the probability of running out of stock, or over stocking woodchip could be calculated, and therefore enabled the management to reduce stockpiles of woodchip significantly.

This dissertation uses a number of different modelling techniques to describe the different elements of the supply chains studied. Literature published on the modelling approaches and analysis used is presented and discussed in the chapters where applicable.

1.2.2 Machine Rate Calculation

Machine rate costing is the estimation of the cost per unit time of a machine, taking into account both fixed and operational costs. Lan (2001) describes this as the calculation of the costs involved in running the machine over its life time. The fixed costs are those which are independent of actual working time, and the variable costs are those which are directly associated with running the machine. Brinker *et al*. (2002) discuss that, because this method is an average cost, the actual fixed costs will be greater early on in the machines life, and less towards the end of its life. The opposite is true for the variable operating costs as efficiency of the machine is probable to decrease, as fuel/lubrication consumption per unit production may increase.

The economic life of the machine and its salvage value must be specified before the annual depreciation can be estimated. The economic life of a machine is its life expectancy. The typical lifespan of harvesting machines is in the region of 4 to 5 years (Brinker et al., 2002). Burgess and Cubbage (1989) describe the salvage value as the residual value of an operating machine at the end of its life. In real terms, it is the value that is expected to resell or trade for at the end of its life. According to Edwards (2002) the salvage value of a machine may change dramatically as new technology is introduced, or a major design change in a machine type may make older machines obsolete. This will have the effect of causing a sharp decline in the remaining value. In general terms, the factors of age and usage hours are usually the most determining factors in salvage value estimation. Brinker *et al*. (2002) suggests that because forest machines are highly maintained, a straight line depreciation method should be used. Because of the high level of maintenance, yearly productivity of forest machines is fairly constant, resulting in uniformity of machine productivity. The machine rates published by Brinker *et al*. (2002) used a salvage of 20% of the purchase price for ease of calculation of depreciation, and salvage value estimation.

Pflueger (2005) describes how investment in machinery requires capital, and therefore a capital cost, whether or not money is actually borrowed to purchase the machinery. If the money is borrowed, the interest cost must be great enough to cover the interest paid on the loan. If the money is not borrowed, an opportunity cost must be applied. According to Edwards (2002), the rate of interest to charge for an opportunity cost will depend on the other options for that investment. At minimum, this rate should be equal to the investment rates of the banking system. Higher rates maybe applicable if other investment opportunities are available, however the risk involved in those investment opportunities is then usually higher.

Whiteman (1999) calculates an annual insurance cost from a percentage of current machine value. This allows for annual insurance cost reduction over time as the machine depreciates. This indicates a need for current machine value to be an input in machine cost modelling. If however, the costing is to be calculated for a system analysis over a number of operations, then the mean annual insurance cost may be required.

In machine rate costing analysis, fuel costs can be represented a number of ways, per m^3, per productive hour, per hectare or, for transportation vehicles, per km. For forest harvesting, productive rates will depend on mean tree size, and therefore a fuel consumption rate per hectare is not preferred. The fuel consumption rate for a machine is mainly a function of the machine's horsepower rating: however, transmission type, machine type, and machine use also influence fuel consumption. Fuel consumption rates can be obtained from dealer specifications. However, historical records are probably a better source as the estimated data from the dealers could be biased towards a better performance. Lubrication (engine oil, hydraulic oil and other lubricants) cost is usually determined as a percentage of fuel costs since horsepower, transmission type, machine type, and machine use also determine the amount of lubrication used (Brinker et al., 2002).

Brinker *et al*. (2002) calculates repair and maintenance costs as a percentage of annual depreciation. This gives a mean cost over the life of the machine. However, Edwards (2002) describes how repair costs are lower in the early life of a machine, and increase as the machine accumulates hours of use. Edwards uses a percentage of new list price determined by accumulated hours use.

Consumable replacement parts (e.g. tyres, chains, service parts) are not calculated in the same manner as repair and maintenance parts. The US Forest Service machine rate calculator (Bilek, 2007) deducts the cost of the consumable parts shipped with the machine from the purchase price, and treats them as consumable operational cost as they have a shorter life span then the machine. The individual consumable item cost is then calculated per hour from their cost and expected life.

Hogg *et al*. (2008) describes how the cost of a laborer includes basic salary, social/fringe benefits, overtime, travel and subsistence etc. It is total cost of employment of a worker to the organization. Items and consumables such as P.P.E (Personnel Protective Equipment) are treated in the same way as machine consumable replacement parts, and are not directly associated with labour cost, even though they may be worker specific.

1.2.3 Machine Productivity Evaluation

Stampfer and Steinmüller (2001) describe how productivity models for harvesting equipment contain three basic components: tree processing, locomotion, and delays. Chipping operations also follow the same logic, as Spinelli and Hartsough (2001) also outline 3 similar components: Chip time, repositioning and delays, but includes another component titled “other”. The “other” component regarded in this case as productive delays such as repositioning or bunching of material for chipping. Forwarder productivity comprises of driving empty, loading, driving loaded, other productive and delay (Nurminen et al., 2006). Importantly the delay component in all respects is a ratio of non productive time to total scheduled work time given from existing historical data, and that to generate a productivity model it is only necessary to capture the data from the work time components. Spinelli and Visser (2009) make the point that there is “an inherent difficulty in obtaining representative samples of a typically erratic phenomenon from a relatively short observation periods.”

Spinelli and Visser (2008) conducted studies to estimate appropriate delay factors for harvesting machines over a range of harvesting systems, and calculated a delay factor of 0.337 for harvesting machines using a standard cut to length system. It was also found that delay factors had increased as time study duration increased i.e: a variation of 27% occurred between studies of less than 10 hours and more than 50 hours. This variation information is presented anecdotally as the sample population encompassed a range of harvesting systems, and more study on single systems would be required to test the hypothesis.

Utilization percentages are often preferred over delay factors when presenting data, for ease of cost analysis, and are directly related. This variable implicates heavily on the costing analysis of harvesting/chipping operations. Brinker *et al* (2002) published utilization rates for 104 different forest machines based on research from previous literature. The rates given do not differ between make and model of machine, only machine type, i.e: a typical utilisation factor has been used per machine type. The figures are synopsised in table 1.2:

Table 1.2: Utilisation rates for forest machine types

Machine Type	Utilisation %
Feller Buncher	65%
Harvester	80%
Skidder	60%
Clambunk Skidder	65%
Forwarder	80%
Loader	65%
Delimber	65%

(Brinker et al., 2002)

Spinelli and Visser (2009) studied chipper operations in Italy, and have published the utilisation percentages in the table 1.3:

Table 1.3: Utilisation rates for chipper types

Machine Type	Utilisation %
Roadside Chipper	74%
Terrain Chipper	75%

(Spinelli and Visser, 2009)

1.2.4 Wood product characterisation

For wood energy products, information on the volume of wood produced is not sufficient. The energy content of the wood must also be estimated. The calorific content of Scandinavian conifer wood chips is given by Serup and Kofman (2005) as:

$$NCV = 19.2 - (0.2164 \times moisture\ content\%\ of\ total\ weight)$$

Where: NCV = Net calorific value in GJ per tonne

Moisture content is required in the net calorific value calculation, and is defined as the water content expressed as a percentage of the total weight of the wood. The oven dry method for determination of moisture content is the most commonly referred method in literature and is well established in industry and research (Purser et al., 1999). Although it requires no specialised equipment, it is slow. An electrical method for determining moisture content of wood uses hand held electrical devices which give a digital readout of the moisture content. Electrical moisture metres are commonly used in the panel board industry as the moisture levels experienced are much lower i.e. after kiln drying. Studies by James (1988) found that:

"As the moisture content decreases from fibre saturation (about 30%, based on dry weight of wood) to the oven dry condition, the conductance decreases by a factor of over 10 million. In this range of moisture content, a roughly linear relationship exists between the logarithm of conductance and the logarithm of moisture content. At moisture levels beyond fibre saturation the electrical conductance correlates very poorly with moisture content".

Also, all electrical devices must be calibrated, from a known true value, and these calibrations would have to encompass a non electrical method, therefore the calibration is only as good as the oven dry method (Simpson and TenWolde, 1999).

Basic Density is defined as the oven dry weight relative to the green volume, expressed as kg/ m^3. It is the amount wood material less the moisture present per unit volume (Thygesen, 1994). The cellular structure of wood determines its basic density. The cell walls of wood have a density of about 1520kg/ m^3. The porosity of wood, largely lumen space in the cells, decreases the basic density depending on the species cellular structure. Interestingly, there is no standard method for determining basic density (Bowyer et al., 2007). Tobin and Nieuwenhuis (2007) used a submersion technique for volume measurement, and an oven dry method to measure the dry mass. Treacy *et al*. (2000) used an x-ray technique which measures the amount of x-ray light passing through samples of wood, converting the measurements to density. Thygesen (1994) used near infrared reflectance (NIR) and transmittance spectrometry to determine basic density. From their study, Tobin and Nieuwenhuis (2007) detail the basic density of Irish grown Sitka spruce in the table 1.4:

Table 1.4: Basic Density of Irish grown Sitka spruce according to age

Age	Basic Density (kg/m^3)	Margin of Error (95 % confidence)
9	475	17.1
14	412.8	53.5
14	375.3	43.33
28	389.3	40.85
30	378.5	57.2
46	365.2	19.25

(Tobin and Nieuwenhuis, 2007)

The data suggests that basic density decreases with age. The confidence intervals suggest that the variability of basic density can be large. Treacy *et al*. (2000) found that when comparing basic density of different provenances of Irish grown Sitka spruce, the variability of basic density within a provenance was greater than the difference between the provenances.

Literature published on the data collection, analysis, and modeling methods used in this dissertation is presented in the relevant sections.

Chapter 2: A taper model and a diameter at breast height to total height model to predict user defined roundwood assortments

2.1 Introduction

Standard forest mensuration practices estimate standing tree volume to merchantable timber height. Merchantable timber height is where the stem tapers below 7 cm diameter (Matthews and Mackie, 2006). The actual volume as cut by a harvesting machine will differ from this estimate in two ways. The volume will be less when cutting to a specified length, as only full log lengths can be processed. For example, a stem of 4.5 m merchantable volume height will only produce one 3 m length log, the other 1.5 m will be lost. The volume will be greater than the estimate when using a full stem assortment, as the full stem includes the material above the height where the stems taper below 7 cm diameter (Keogh, 1987). In Sitka spruce first thinning, an average of 26% additional biomass was recovered in energywood harvesting, where the whole stem was processed into variable lengths, compared to harvesting standard roundwood assortments (Kent *et al.*, 2011).

Research into the taper of forest trees is documented as far back as 1913 (Stoehr, 1955), but perhaps some of the earliest functions constructed for prediction purposes are from work in British Colombia (Newnham, 1958). By 1969, it was well recognised that a total volume per hectare estimate was no longer sufficient for harvest planning. It was necessary to be able to estimate the volume of specific log sizes and also the number of logs that could be produced from a growing forest. At first, it was thought that additional upper stem measurements would need to be taken during inventory fieldwork. However, after the development and testing of a number of taper equations, it was proven that the modelling of the stem could produce accurate results without the need for upper stem measurements (Kozak *et al.*, 1969). Since then taper functions have been used across the globe for predicting upper stem diameters and log volumes. They are frequently used in inventory and growth modelling projection systems due to their flexibility and ability to estimate multi product volumes (Trincado and Burkhart, 2006). Most recently, Fonweban *et al*. (2011) developed taper equations for Scots pine and Sitka spruce in Northern Britain. In Ireland Nieuwenhuis *et al*. (2005) used a taper equation as part of a value maximisation decision support tool in the sawmill production chain.

Taper is defined as, "the rate of narrowing in diameter with relation to increase in height of a given "shape" (Gray, 1956). In forestry the tree shape is referred to as the form. Different taper equations use different forms to describe the stem. The form of trees is generally regarded as comprising of a number of shapes: the lower section near the butt being a frustum of a neiloid, the middle section being a frustum of a paraboloid, and the top section being a paraboloid (Avery and Burkhart, 1983). Many of the more complex taper models use a number of polynomial functions joined together to recreate the stem form (Trincado and Burkhart, 2006). Some models will fit different trees species and conditions better than others, so it is beneficial to test a number of models with the data to find the best fit, as per Walters and Hann (1986). According to Kozak (2004), taper equations are superior to volume equations, as volume equations only estimate total or merchantable volume, whereas taper equations provide estimates of: "i) diameter at any point along the stem, ii) total stem volume, iii) merchantable volume to any top diameter, iv) merchantable height to any top diameter, v) individual volumes for logs of any length at any height from the ground)"

The aim of this study was to develop a set of models which can be used as a tool to predict stem volumes in Sitka Spruce first thinning trees. This tool may be of benefit to private forest managers in the planning phase of thinning operations. The tool has the potential to assist the manager in optimizing the value of thinnings through market selection of the timber before harvesting. The tool can be used to simulate the harvest volume from user specified assortment dimensions. Harvesting methods could then be selected that best match the optimal return from the forest. The tool was developed in two distinct parts; a taper model and a dbh to height model.

2.2 Materials and methods

2.2.1 Data collection

The data was collected on five sites; three sites in the West of Ireland, one in the midlands and one in the South. The ages of the stands varied between 13 and 20 years, and were even aged Sitka spruce monocultures, except for one site which had an intimate mixture of Japanese larch. The Japanese larch was not used in this study. In order to validate the model, site 5 was chosen at random as the validation site. The models were therefore developed with the data from sites 1-4. In total, 429 sample trees were felled and measured. Sampling occurred in lines where approximately 30 trees were selected per line. The lines were picked randomly throughout each site. Table 2.1 details the site descriptions and the number of sample trees taken on each site. The sample trees were felled by chainsaw and measured for total height and dbh. Total height was measured with a loggers tape to the nearest centimetre, and the diameter at breast height measured to the nearest rounded down centimetre using a callipers. The stem was marked at one metre intervals from the base to the tip and the mid-diameter point of each interval recorded to the nearest rounded down centimetre.

Table 2.1: Site Characteristics

Site Number	Site Location	Site Area	Age	Stocking	Mean Dbh	Top Height	Yield Class	No. of Sample trees
		ha	years	stems ha^{-1}	cm	m	m^3 ha^{-1} yr^{-1}	
1	Abbyfeale, Co. Limerick	9.8	20	2191	17	13.5	22	90
2	Ballybofey, Co. Donegal	21	13	2455	14	11.2	24	75
3	Bweeng, Co. Cork	10	17	2251	13	11.1	23	88
4	Toormakeady, Co. Sligo	14	16	2624	13	10.9	24	90
5	Woodberry, Co. Galway	26.6	17	2199	15	12.3	24	90

2.2.2 Fitting non linear regressions

The process of fitting non-linear equations in other publications has largely been done with the SAS NLIN or PROC NLIN procedure: a macro designed for the SAS statistical software package (Petersson, 1999, Sánchez et al., 2003, Fekedulegn et al., 1999, Sharma and Zhang, 2004, Jiang et al., 2005, Ounekham, 2009, Dieguez-Aranda et al., 2006, Huang and Price, 2000, Schröder and Álvarez González, 2001, Lei et al., 2009, Fang and Bailey, 1998, Fonweban et al., 2011, Zhou et al., 2007). In this study the MINITAB 16 statistical package was used as it also has the ability to perform non linear regressions (Minitab, 2010). Non linear regression is an iterative procedure, meaning that the computer program adjusts the model numerous times in order to find the best fit (Neter *et al.*, 1996). In order to do this, the program must have a starting value for each parameter. From these starting values, the model is adjusted until the best fit is found. These values need to be sufficiently close to what the final estimates will be. (Keogh, 1987). There is no formal procedure for assigning starting values, they are usually set by a researchers own experience, or taken from literature as has been done in this study (Motulsky and Ransnas, 1987).

2.2.3 Taper equations

Three equations were tested for their suitability for modelling the taper of Sitka spruce farm forestry first thinnings in Ireland. Table 2.2 details the taper models tested in this study.

Table 2.2 Taper Models

Model Number	Model	Reference
1	$d = \beta_1 dbh^{\beta_2} x^{[\beta_3 z^2 + \beta_4 \ln(z+0.001) + \beta_5 (\frac{dbh}{ht})]}$	(Kozak, 2004, Fonweban et al., 2011)
2	$d = \beta_1 dbh^{\beta_2} (1-z)^{\beta_3 z^2 + \beta_4 + z + \beta_5}$	(Lee et al., 2003)
3	$\left(\frac{d}{dbh}\right)^2 = \beta_1 \left(\frac{h}{h_{dbh}}\right)^{2-(\beta_2+\beta_3 x+\beta_4 x^2)} \left(\frac{ht-h}{ht-h_{dbh}}\right)$	(Sharma and Zhang, 2004)

Where: $d = predicted\ diameter\ (cm)$, $x = \frac{1-\sqrt{z}}{1-\sqrt{p}}$, $p = point\ of\ inflection = \frac{1.3}{ht}$,
$ht = total\ tree\ height\ (m)$, $h = height\ along\ the\ stem\ at\ predicted\ diameter\ (m)$, $z = \frac{h}{ht} = relative\ height\ of\ predicted\ diameter$,
$dbh = diameter\ at\ breast\ height\ (cm)$, $h_{dbh} = breast\ height\ (m)$,
$\beta_1 to\ \beta_5\ are\ the\ parameters\ to\ be\ estimated\ from\ the\ regression\ analysis$

2.2.4 Dbh to total height equations

Four equation forms were trialled for their suitability. Table 2.3 details the equations trialled in the study. Model 7, The Chapman Richards model, as cited by Kershaw *et al.* (2008), does not use any stand variables as an input, unlike the others which use top height, or quadratic mean dbh. However, Twomey *et al.* (2007b) in the Irish National Forest Inventory (NFI), fit this model to nationwide Sitka Spruce data taken from plots throughout Ireland, and referred to it as a *global model*. Twomey *et al.* then improved the predictive capabilities of the model by localising it to the plot level using sample height tree measurements. This was accomplished by fixing β_2 and β_3, and running another non linear regression to estimate β_1. In this study the model was fitted in the same way: the model was parameterised using the data from sites 1 to 4, and during validation a sample height and the dbh of the sample height tree was used to localise the model. It must also be noted that the NFI locked β_3 to a value of 0.7 in 84% of the cases in which the Chapman Richards model was used during their study, and this was also trialled in this study.

Table 2.3: Dbh to total height models

Model Number	Model	Reference
4	$h = 1.3 + (\beta_1 + \beta_2 H_0 - \beta_3 D_g)e^{\beta_4/dbh}$	(Mirkovich, 1958)
5	$h = 1.3 + \beta_1 dbh^{\beta_2}$	(Fang and Bailey, 1998)
6	$h = 1.3 + (H_0 - 1.3)e^{\beta_1(1-\frac{D_g}{dbh})+\beta_2(\frac{1}{D_g}-\frac{1}{dbh})}$	(Gaffrey, 1988)
7	$h = 1.3 + \beta_1(1 - e^{-\beta_2 dbh})^{\frac{1}{\beta_3}}$	(Kershaw Jr et al., 2008)

Where: $h = total\ height\ of\ the\ tree$, $H_0 = stand\ top\ height$, $D_g = Quadratic\ mean\ diameter\ at\ breast\ height\ of\ the\ stand$, $dbh = diameter\ at\ breast\ height\ of\ the\ tree$

β_1 *to* β_4 *are the parameters to be estimated from the regression analysis*

2.2.5 Model evaluation and validation

The models were evaluated for their ability to fit to the data sets by assessing the RMSE (*Rooted Mean Square Error)* from the output of the regression analysis, as per Fonbewan (2011). As recommended in the publication: *Standards for evaluating taper estimating systems*, by Kozak and Smith (1993), the models were evaluated for their prediction abilities and were compared to the independent validation data sets for bias and standard error estimate.

Average bias was defined as:

$$Mean\ Bias = \frac{\sum_{i=1}^{n} (Y_i - \widehat{Y_i})}{n}$$

Where Y_i = actual observation, $\widehat{Y_i}$ = predicted value of the actual observation, and n = number of observations.

The standard error estimate is given as

$$Standard\ Error\ Estimate = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \widehat{Y_i})^2}{n-k}}$$

Where Y_i = actual observation, $\widehat{Y_i}$ = predicted value of the actual observation, n = number of observations, and k = number of estimated parameters (Jiang et al., 2005).

2.3 Results and discussion

2.3.1 Taper model

Table 2.4 details the parameter estimates for each taper model trialled in the study, and the associated 95% confidence interval for each estimate. The Rooted Mean Square Error (RMSE) is also displayed for each of the regressions. Models 1 and 2 both gave similar RMSEs, while model 3 has a value which is much lower. It must be noted that the actual output of model 3 is a squared relative diameter (as opposed to an actual diameter in centimetres), and therefore cannot be directly compared to the other two models. Kozak's model was fitted to Sitka spruce in the UK with a RMSE of 0.983 cm, similar to the 1.001cm in this study (Fonweban *et al.*, 2011).

Table 2.4: Dbh to total height models

Model	Parameter Estimate (with 95% Confidence Intervals)					RMSE
	β1	β2	β3	β4	β5	
1	1.14369 (1.10540, 1.18341)	1.00093 (0.98956, 1.01231)	-0.15975 (-0.20687, -0.11306)	1.30694 (1.23812, 1.37624)	0.06093 (0.03453, 0.08752)	1.001 cm
2	1.38031 (1.33811, 1.42372)	0.94242 (0.93196, 0.95292)	0.69881 (0.46053, 0.94036)	-0.88739 (-1.19243, -0.58470)	1.25515 (1.15248, 1.35817)	0.997 cm
3	0.26648 (0.26360, 0.26936)	2.19697 (2.17323, 2.22080)	-0.13796 (-0.34731, 0.06853)	-0.82589 (-1.12463, -0.53628)		0.151*

* Squared relative diameter

To assess the models prediction abilities, each model was used to estimate diameters at specified one metre intervals on the validation data. The validation data comprised of 89 trees, a total of 979 predictions. The results were then compared to the actual measured stem diameters of these trees as observed in the field. The input data to the models were the dbh and total height as measured for each tree. Detailed in table 2.5 are the standard error estimates (SEE) and mean bias from the results. The data is grouped by each 10% increment of relative height to enable comparisons along the stem. The data shows that model 3 has a large mean bias for the lower portion of the stem. Both model 1 and 2 have similar SEE, but model 1 performed better in terms of mean bias overall, and also on the majority of the individual diameters up the stem. For these reasons it was model 1, Kozaks model, which was chosen as the best for this study.

Table 2.5: Prediction statistics for parameterized taper models using validation data

		Model 1		Model 2		Model 3	
Relative height %	n	SEE (cm)	Bias (cm)	SEE (cm)	Bias (cm)	SEE (cm)	Bias (cm)
0-10	99	1.07	0.09	1.09	-0.16	0.53	6.92
10-20	168	0.53	-0.38	0.53	-0.41	0.27	6.26
20-30	90	0.86	-0.13	0.87	-0.16	0.43	5.9
30-40	93	0.83	0.08	0.84	-0.05	0.41	5.26
40-50	91	0.83	0.38	0.87	0.1	0.41	4.95
50-60	88	0.84	0.34	0.9	0.0	0.41	4.16
60-70	90	0.83	-0.08	0.94	-0.4	0.39	3.03
70-80	90	0.73	-0.22	0.83	-0.37	0.35	2.09
80-90	89	0.6	-0.38	0.69	-0.24	0.28	1.09
90-100	81	0.46	-0.1	0.48	0.29	0.23	0.59
Overall	979	0.85	-0.06	0.85	-0.17	0.49	4.28

2.3.2 Dbh to total height model

Four models were tested for their suitability in the study. The parameter estimates and associated confidence intervals are detailed in table 2.6. The ranking of the models by their RMSE favours model 4, followed by model 7.

Table 2.6: Parameter estimates for dbh to total height models

Model	Parameter Estimate (with 95% Confidence Intervals)				RMSE
	β1	β2	β3	β4	
4	1.84044 (0.07422, 3.64110)	0.44507 (0.33215, 0.55901)	-0.41460 (-0.54718, -0.28104)	-5.12417 (-5.59778, -4.65741)	1.018
5	2.59149 (2.30549, 2.90877)	0.4687 (0.42564, 0.51207)			1.231
6	0.246935 (0.21529, 0.279207)	-0.213148 (-1.25467, 0.814186)			1.45
7	10.8599 (10.4688, 11.2950)	0.1558 (0.1427, 0.1703)	0.7 (locked)		1.187

The validation data was collected from three plots on a single site. The stand level variables for each plot were input to the models as required. Model 7 was localised to each plot through non-linear regression as described in the methodology section. The data of the results is displayed in table 8. The data gives no clear ranking of the models from the SEE and Bias, but all models have shown to have an SEE of below 1.0 cm. The error range of each model shows that on all sites, model 7, the Chapman Richards model, performed the best and was chosen for use in this study.

Table 2.7: Statistics for parameterized dbh to height models using validation data

	Top Height	QMDBH	Dominant dbh	Model 4			Model 5			Model 6			Model 7 (localised)		
	(m)	(cm)	(cm)	SEE (m)	Bias (m)	Error range (m)	SEE (m)	Bias (m)	Error range (m)	SEE (m)	Bias (m)	Error range (m)	SEE (m)	Bias (m)	Error range (m)
Plot 1	13.6	12.1	21	0.76	0.89	4.6 (-1.8,2.8)	0.7	0.68	4.4 (-1.7, 2.7)	0.91	-0.77	4.4 (-3.5, 0.9)	0.99	-0.67	4.3 (-3.5,0.8)
Plot 2	9.7	13	22	0.59	0.26	3.7 (-1.7,2.0)	0.74	-0.72	3.6 (-2.6, 1.0)	0.55	0.92	3.8 (-1.1,2.7)	0.6	0.91	3.6 (-1.0, 2.6)
Plot 3	13.7	15.6	23	0.79	0.53	6.0 (-2.8,3.2)	0.92	1.37	6.0 (-1.8, 4.2)	0.9	-0.07	6.2 (-3.5,2.7)	0.92	-0.26	5.9 (-3.4,2.5)

2.3.3 Complete prediction tool

The parameterised Chapman Richards model, model 7, was localised by adjusting β_1. This was done using a sample height measurement and the associated dbh of the sample height tree. Ideally, a number of trees would be measured for height and used for the adjustment. However, it was found that there were two benefits to using only one tree: i) It requires minimal additional measurement, ii) the adjusted parameter of β_1 can be found mathematically without non-linear regresson.

As the majority of forest managers will not have access to non linear regression tools, it was important that the models were combined into a stand-alone entity that could be implemented into a simple spreadsheet software package. As all other terms in the equation are known, it was possible to rewrite the equation to find β_1. This gives the tool the ability to automatically localise to a plot by adding the terms of *sample height taken in the stand* (sH) and the *dbh of the sample height tree* (dbh_{sH}) to the equation. The modification of the model is outlined below:

$$\text{If total height } (H) = 1.3 + theta1 \times (1 - e^{-0.155793dbh})^{\frac{1}{0.7}}$$

Then using the sample height (*sH*) and the dbh of the sample height tree (dbh_{sH}), the equation can be rewritten as the following to find β_1:

$$\beta_1 = (sH - 1.3)/(1 - e^{-0.155793dbh_{sH}})^{\frac{1}{0.7}}$$

And therefore total height can be found from:

$$H = 1.3 + \left[(sH - 1.3)/(1 - e^{-0.155793dbh_{sH}})^{\frac{1}{0.7}}\right](1 - e^{-0.155793dbh})^{\frac{1}{0.7}}$$

Where: H = total height, dbh = diameter at breast height (cm), sH = sample height (m), dbh_{sH} = dbh of the sample height tree (cm).

Using a combination of the Kozak taper equation and Chapman Richards dbh to height model, parameterised for Irish Sitka spruce first thinnings in this study, and modified to localise the dbh to height relationship, an equation to predict upper stem diameters of Irish Sitka spruce trees in first thinnings is formed as:

$$d = 1.14369 dbh^{1.00093} x^{[-0.15975z^2 + 1.30694\ln(z+0.001) + 0.06093(\frac{dbh}{ht})]}$$

Where: $d = predicted\ diameter\ (cm)$, $ht = total\ tree\ height\ (m)$ =

$1.3 + \left[(sH - 1.3)/(1 - e^{-0.155793 dbh_{sH}})^{\frac{1}{0.7}}\right](1 - e^{-0.155793 dbh})^{\frac{1}{0.7}}$, $x = \frac{1-\sqrt{z}}{1-\sqrt{p}}$,

$z = \frac{h}{ht} = relative\ height\ of\ predicted\ diameter$, $p = point\ of\ inflection = 1.3/ht$,

$h = height\ along\ the\ stem\ at\ predicted\ diameter\ (m)$, $dbh = diameter\ at\ breast\ height\ (cm)$, $sH =$ $sample\ height\ taken\ in\ the\ stand\ (m)$, $dbh_{TH} = dbh\ of\ the\ sample\ height\ tree$

This equation can be used as a tool to determine which log assortments can potentially be cut from the stem. This can be accomplished by predicting stem diameters at heights corresponding to the assortment lengths, and assessing whether the diameters are above the minimum top diameter threshold. All calculations can be made in a simple spreadsheet.

2.3.4 Validation of the prediction tool for estimating stem volume

The prediction tool was validated using the data set from site 5. The stem volumes were estimated in 1 m sections from the base to the tip. The results in table 2.8 show that residual error and bias is low. The standard error estimate overall is 0.0098 m^3 per tree. The overall mean bias is small, at 0.00003 m^3. A scatterplot of the predicted versus measured volumes is presented in figure 2.1.

Table 2.8: Statistics from the prediction tool using the validation datasets

	Top Height (m)	QMDBH (cm)	Mean Stem vol (m^3) (measured)	SEE per stem (m^3)	Mean Bias per stem (m^3)	Predicted Total Volume per plot (m^3)	Measured Total volume per plot (m^3)
Plot 1	13.60	12.10	0.06	0.0112	-0.003	1.84	1.74
Plot 2	9.70	13.00	0.06	0.0064	0.003	1.58	1.65
Plot 3	13.70	15.60	0.11	0.0102	0.001	3.18	3.20
Overall				0.0098	0.00003	6.587	6.589

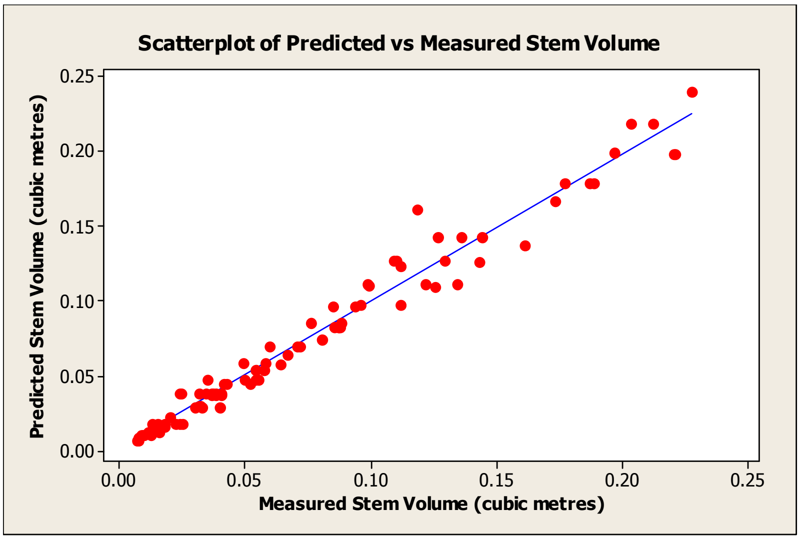


Figure 2.1: Predicted versus Measured Stem Volume (m^3) of the Validation Dataset

<u>2.3.5 Application of the prediction tool to estimate assortment volumes</u>

The developed prediction tool only utilises data collected in a standard thinning control assessment, as described by Matthews and Mackie (2006). Consider a stand of Sitka spruce ready for first thinning. The top height tree was measured as having a height of 13.7 m with a dbh of 20 cm. Four 100 m^2 plots were set out and the dbh of every tree marked for thinning within the plots was recorded. The data collected is presented in table 2.9.

Each measured dbh is presented in a distribution table. The total stem volume per tree and merchantable volume to 7 cm top diameter per tree are estimated in 1 m length sections for each dbh class. The harvestable volume per tree in each diameter class of two standard roundwood assortments is estimated. The pallet assortment is defined as a 2.5 m length and a minimum top diameter of 14 cm, and pulp is defined as a 3.0 m length and minimum top diameter of 7 cm. Other roundwood assortments could also be defined by assortment length and minimum top diameter. Based on the height and dbh of the top height tree and the diameter distribution of trees marked for thinning in the four plots, the prediction tool estimated a whole stem volume of 80 m^3/ha, a volume to 7 cm diameter of 74 m^3/ha, and a volume of cut to length assortments of 25 m^3/ha for pallet, and 44 m^3/ha for pulp, yielding 69m^3/ha of roundwood.

Table 2.9: Example of the application of the prediction tool to estimate volume of assortments

		Per tree		Per Hectare					
dbh	Frequency	Stem vol	Merch vol.	Stem vol.	Merch vol.	Pallet vol.	No. pallet logs	Pulp volume	No. pulp logs
7	1	0.016	0.006	0.4	0.2	0	0	0	0
11	2	0.048	0.040	2.4	2.0	0	0	1.4	50
12	1	0.059	0.051	1.5	1.3	0	0	0.9	25
13	2	0.071	0.063	3.6	3.2	0	0	3.1	100
14	2	0.084	0.076	4.2	3.8	0	0	3.6	100
15	7	0.098	0.090	17.2	15.8	0	0	14.5	350
16	2	0.113	0.105	5.7	5.3	2.7	50	1.9	50
17	4	0.129	0.121	12.9	12.1	6.1	100	4.3	100
18	3	0.146	0.138	11.0	10.4	5.1	75	5.3	150
19	4	0.163	0.156	16.3	15.6	7.6	100	7.9	200
20	1	0.182	0.175	4.6	4.4	3.4	50	0.8	25
			Totals per hectare	80	74	25	375	44	1150

Sample tree height: 13.7m, dbh of sample height tree: 20 cm. Volumes in m^3. Predicted using 4 x 100m^2 plots.

2.4 Concluding remarks

For Sitka spruce first thinning plantations in Ireland, Kozak's taper equation performed best at predicting diameters along the stem. To estimate the total height of the trees, the Chapman

Richards equation performed best when localised using a sample height measurement in the plot, and the dbh of the sample height tree. Together, the taper function and dbh to height function can be used as an informative tool to predict the volume of different assortments in a stand prior to thinning. The prediction tool requires sample plot data from a forest, where the dbh of every tree to be thinned in the plot is measured, and one tree in the plot is measured for dbh and total height. The prediction tool does not require any additional measurements beyond those normally taken in the thinning control measurement procedure. Overall, when compared to the validation data, the tool predicted the full stem length volume with a SEE 0.0098 m^3 per tree, and a bias of 0.00003 m^3 per tree. The tool can be used for trees between 5 cm to 30 cm dbh, and for heights of between 5.1 m to 16.0 m. With more data, the tool could easily be improved to predict outside these ranges.

This prediction tool can help forest managers plan the timing of first thinning, the harvesting resource capacity required and the identification and marketing of product to customers in non-industrial private forests. In addition, the tool could be further developed with the relative prices of roundwood and energy markets to choose a harvesting method that will provide optimal return from the forest thinning operation. Where a wood energy market is preferred, the tool can estimate the additional volume recovered by harvesting the whole stem and cross-cutting in variable lengths rather than maintaining the assortment specification required by the panel board sector but not necessary for woodchip.

Chapter 3: Simulating the tree size distribution of trees harvested in a line and selection first thinning

3.1 Introduction

The volume of the average tree in a stand is not appropriate for directly estimating assortment volumes, as some log products will only be present in the upper ends of the dbh distribution (Dieguez-Aranda et al., 2006). Nor is dbh normally distributed in a standing forest (Kangas and Maltamo, 2000), and so, unequal proportions of tree sizes will be represented by the average. Forest growth models often use dbh distributions to form more informative forecasts than total volume, predicting the volume of assortment types (Qin and Cao, 2006). In general, stand level growth models project a small number of stand variables (such as basal area, top height and number of trees per hectare), over time. Separate models must be developed for different species and silvicultural treatment (such as spacing, monocultures/mixtures, even age etc.) The rate of change of the variables depends on an index of growth (such as yield class and site index) (García, 1988). A set of functions are used to calculate the variable values at a point in time, and then another system of functions can be implemented to describe the volume. The volume functions can be a basic system to estimate volume at the stand level from basal area and a measure of height (such as form height), or a more complex system using a dbh distribution, dbh/height model, and a taper equation, to estimate volume at a tree level (Vanclay, 1994). The use of these three functions together (a dbh distribution, dbh/height model, and a taper equation) has been referred to in growth modelling as a disaggregation system (Dieguez-Aranda et al., 2006). Whilst this study is not concerned with the change in stand variables over time, the possibility to disaggregate stand parameters is useful as will be discussed.

The dbh distribution of stands according to their mean dbh is available in published stand tables, which document the frequency of every dbh interval (Avery and Burkhart, 1983). However, a problem arises when trying to describe a thinning distribution. A purely systematic thinning does not change the shape of a distribution, as all trees are selected randomly, and therefore the before thinning, thinning and after thinning dbh distribution will have the same shape. On the other hand, any selection of the trees in a thinning will cause a change, as the trees are not chosen randomly, they are chosen to some prescribed silvicultural practice (Von Gadow and Hui, 2001). A typical line and selection first thinning in Ireland is suggested to increase the after thinning mean dbh by 2 cm, a result of a removal of a higher proportion of the smaller trees in the stand (Booth et al., 2007). In this study a set of transition functions will be developed, which will predict the thinning distribution from the before thinning distribution.

The aim of this chapter was the simulation of thinning dbh distributions which are representative of a line and selection first thinning when; either standing inventory data is available, or where the Weibull parameters can taken from published forestry stand tables. Using the simulated dbh distributions, and the dbh/height model and taper equation developed in chapter 2, a stem profile for every tree harvested can be predicted.

3.2 Materials and Methods

3.2.1 Deriving the Weibull parameters of the main crop dbh distribution from published British Forestry Commission stand tables

The British Forestry Commission (BFC) has published dbh frequency tables for conifer plantations at a range of mean dbh levels. A portion of these frequency tables is transcribed in table 3.1.

Table 3.1: BFC stand table for conifers. (percentage distribution of number of trees)

	dbh class (cm)					
Mean dbh (cm)	5	10	15	20	25	30
10	19	71	10			
11	8	73	19			
12	3	66	29	2		
13	1	53	42	4		
14		39	53	8		
15		26	60	14		
16		16	61	21	2	
17		9	57	30	4	
18		5	50	38	7	
19		2	41	45	11	1
20		1	31	50	16	2
21			23	51	22	4
22			16	48	29	7

The diameters for the given dbh classes are the central values for each class.

The Weibull probability function has been used extensively in modelling the dbh distribution of forest stands worldwide (PalahÃ et al., 2006, Gorgoso et al., 2008, Magnussen, 1986). The three parameter Weibull probability density function is defined by Merganič and Sterba (2006) as:

$$f(x) = \frac{\propto}{\beta}((x-T)/\beta)^{\propto-1} \times e^{-\left(\frac{x-T}{b}\right)^{\propto}}$$

Where: T is the threshold parameter, $\propto$ is the shape parameter, and β is the scale parameter.

The Stat Fit statistical program was used to fit the Weibull distribution function to the frequency tables of mean dbh 10 cm to 22 cm inclusive. A dbh of 22 cm was used as the upper threshold as above this level includes dbh values that are outside the reliable use of the taper equation developed in chapter 2. The maximum likelihood estimate method was used in the distribution fitting. This method has been used to fit functions to dbh distribution in other studies (Maltamo et al., 2000). The shape and scale parameters were fit with the computer program, the threshold parameter, as advised by Cao (2004), was set to half the minimum dbh in a dataset.

To be compatible with the taper and dbh to height models developed in chapter 2, a localisation of the dbh to height relationship was required. Dieguez-Aranda *et al.* (2006) describes how the local dbh to height relationship is parameterised in dynamic growth models for generalised height equations from the dominant diameter and the dominant height (top height) of the stand, where the dominant diameter is estimated from the dbh distribution. The dominant diameter can therefore be estimated from the 100 largest dbh values as predicted by the Weibull function for each stand mean dbh size (once the stocking is known). The dominant height (top height) was not given in the stand tables, and so was estimated using a mean dbh to top height relationship. The British Forestry Commission yield tables give the mean dbh and top height predicted for a given age according to yield class. A portion of the published yield tables are transcribed in table 3.2.

Table 3.2 : British Forestry Commission Yield table for SS, no thin, 2 m spacing, yield class 16

YC	Age	Top Height	Tress/ha	Mean dbh	BA/ha	Mean vol	Vol/ha	% mortality	MAI vol/ha	Age
16	17	7.6	2303	12	26	0.03	75	0	4.4	17
16	22	10.8	2232	15	37	0.07	156	0	7.1	22
16	27	13.9	2002	17	46	0.13	258	1	9.6	27
16	32	16.8	1734	20	53	0.21	369	3	11.5	32
16	37	19.6	1515	22	58	0.31	477	5	12.9	37
16	42	22	1336	24	62	0.43	574	7	13.7	42
16	47	24.1	1203	26	66	0.55	660	9	14	47

By plotting the top height versus the mean dbh as published in the tables, it is apparent that the British Forestry Commission has used a modelled relationship, regardless of yield class and age. A plot of the data for all yield classes of SS, no thin, 2m spacing is displayed in figure 3.1. A cubic model explains total variation in the relationship with an R-squared of 100%, indicating the purely mathematical relationship between the sole dependant and independent variables. The cubic model is estimated as:

$$Top\ height = -59.71 + 10.74dbh - 0.3412dbh^2 + 0.004333dbh^3$$

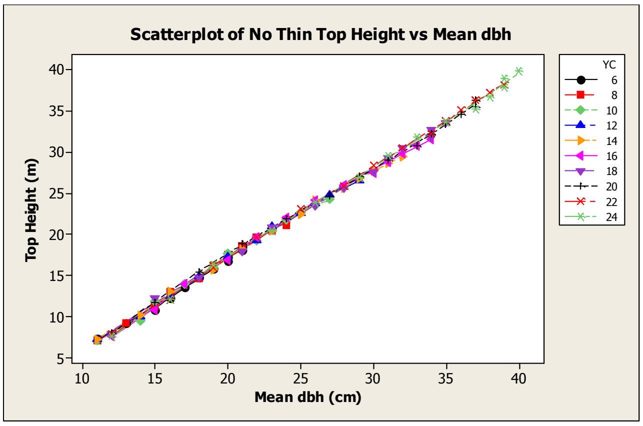


Figure 3.1: Relationship between no thin top height and mean dbh as observed in the British Forestry Commission yield tables

3.2.2 Regression of the Weibull shape and scale parameters

Data was collected on three Sitka spruce plantations in Ireland which underwent a line and selection thinning. Table 3.3 details the site descriptions.

Table 3.3: Site characteristics

Site Location	Site Area	Age	Stocking	Mean Dbh	Top Height	Yield Class
	ha	years	stems ha^{-1}	cm	m	m^3 ha^{-1} yr^{-1}
Abbyfeale, Co. Limerick	9.8	20	2191	17	13.5	22
Bweeng, Co. Cork	10	17	2251	13	11.1	23
Woodberry, Co. Galway	26.6	17	2199	15	12.3	24

Plots were used to compare the before thinning dbh distribution and the after thinning dbh distribution. The plots were marked with paint, so that their location was identifiable after the harvesting. The dbh of every tree in each plot was measured with a callipers, to the nearest rounded down centimetre, before and after thinning. A total of 29 plots were used; 9 from the Abbeyfeale site, 8 from the Bweeng site, and 12 from the Woodberry site. As described by

Murray and von Gadow (1991), the frequency of a diameter class that is thinned can be estimated from:

$$fT_i = fBT_i - fAT_i$$

Where:

fT_i = frequency of ith class of the thinning distribution

fBT_i = frequency of the ith class of the before thinning distribution

fAT_i = frequency of the ith class of the after thinning distribution

The diameter classes were set as 1cm wide, making each class equivalent to a rounded dbh measurement. This gave for each plot; a before thin dbh frequency distribution and a thinning dbh frequency distribution.

A regression analysis was performed, in the Minitab statistical software package to investigate the relationship between the before thinning and thinning Weibull shape and scale parameters. The threshold parameter remains unchanged from thinning, as it represents the minimum allowable value for the function. The before thinning stand parameters were then used with the regression equations to estimate the thinning parameters.

3.2.3 Simulation of thinning dbh datasets

The Weibull parameter estimates for thinning distributions were used to create dbh distributions at each mean dbh level (10 cm to 22 cm). A before thinning distribution, and thinning distribution, were simulated at each mean dbh level. This was accomplished using a Monte Carlo simulation method in the Minitab statistical software package. The Weibull parameter regression equations, detailed previously in this chapter, were developed from plot data which had an average stocking of 2346 trees per hectare, and an average removal percentage of 32% of the main crop, equating to 751 trees removed per hectare. These densities were used in the Monte Carlo simulation as the number of iterations for each dataset, so that, the before thinning datasets contain 2346 values, and the thinning datasets contain 751 values. In this manner, the simulated datasets are reflective of the thinning operation carried out on the trial sites.

3.2.4 Estimation of the volume from a thinning at each mean dbh level

The thinning dbh dataset at each mean dbh level was used with the taper and dbh/height equations developed in chapter 2 to predict assortment volumes. The predicted dominant height and dominant dbh for each dataset were used to localise the dbh/height model. The volumes of the cut to length assortment dimensions that were specified are detailed in table 3.4.

Table 3.4: Assortment dimensions for volume predictions

Assortment	length (m)	Min small end diameter (cm)
Large sawlog	4.9	20
Small sawlog	2.5	14
Pulp	3.0	7

A hierarchy was set out as to which cut to length (CTL) assortments were given priority for volume estimation. The hierarchy was set out as follows: i) large sawlog, ii) small sawlog, iii) pulp.

To clarify this, it may be useful to consider the calculations used with the taper equation as virtually cross cutting each stem when it made CTL volume predictions. If sawlog (the top hierarchy) is present in the stem, that portion of the stem is allocated to that assortment and its volume is calculated. The same portion of the stem cannot then be allocated to another CTL assortment. The hierarchy is set place so that the most desirable assortment is tested for first, followed by the second, and then the third.

An estimation of whole the tree volume (the volume of the full stem and branches) was estimated by use of a biomass expansion factor. Biomass expansion factors estimate the total aboveground biomass from the merchantable volume biomass. The most suitable biomass expansion factor identified from literature is an equation published by Levy *et al*. (2004). This equation operates at the tree level, and adjusts the biomass expansion factor according to tree height, as opposed to a static factor for all tree sizes. Levy's biomass equation was developed in the UK for conifer species from a large dataset of over 2000 uprooted trees, illustrated in figure 3.2.

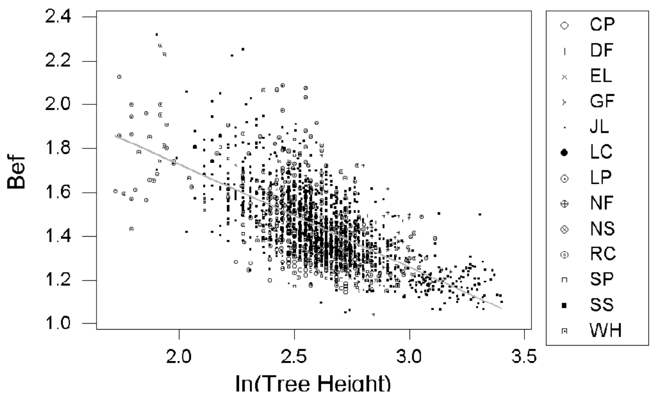


Figure 3.2: Dataset and regression developed for BEF developed by Levy *et al.* (2004)

The equation uses a mixed modelling approach, incorporating species as a random variable when all others were fixed. This gives a species specific intercept for the equation, and so can be localised for Sitka spruce as required in this study. Another benefit of the Leevy equation is its inclusion of dead branches, which is not common for biomass expansion factors as their primary role is in estimating carbon sequestration. The assumption that must be made when using a biomass expansion factor to predict volume is that the basic density within the stem is the same as the basic density in the branches, as per Kent *et al.* (2011).

The Levy equation is given as:

$$Bef = 2.711 - 0.4812(ln(h_{tree}))$$

(Levy et al., 2004)

Where

Bef = Ratio of total aboveground biomass to merchantable stem biomass of Sitka spruce (kg)

h = Total tree height in metres

This biomass expansion factor was then simply incorporated into the volume calculations described in chapter 2, as:

$$Whole\ tree\ volume\ (m^3) = Merchantable\ volume(m^3) \times (2.711 - 0.4812(ln(h_{tree})))$$

For each thinning dataset, the merchantable volume, whole tree volume, and cut to length volumes were predicted at the tree level. The total volume predicted for each thinning dataset was predicted from the sum of the tree volumes.

3.3 Results and discussion

3.3.1 Regression of the Weibull Parameters

The Weibull distribution fitted to all measured plot data significantly at an alpha level of 0.05 using an Anderson Darling goodness of fit test. The overall mean stocking in the plots was 2346 trees per hectare. The average removal percentage was 32% of the main crop. The regression analysis tested the relationship between the thinning Weibull parameters and a number of possible predictors. The predictors tested were: the before thinning Weibull parameters, the stocking, the post thinning stocking, the mean dbh, and the removal percentage. Only the before thinning parameters were seen as significant. A regression equation for both the thinning alpha Weibull parameter and the thinning beta Weibull parameter was formed. The threshold parameter was fixed and remained unchanged from thinning. The regression equations took the form of a simple straight linear model:

$$Thinning\ Weibull\ Parameter_i = \beta_0 + \beta_1 Before\ Thinning\ Weibull\ Paramater_i$$

Table 3.5 details the fit statistics for the regression equations formed in the analysis. The R squared values are both high, at above 70%. The overall p values for the regression equations were both 0.000. Figure 3.3 and figure 3.4 display scatter plots of the data, which include the straight regression line of the thinning shape and scale models.

Table 3.5: Fit statistics for regression of the Weibull shape and scale parameters

Model	β_0	SE	P value	β_1	SE	P value	R^2
Thinning Alpha	0.627	0.35	0.09	1.018	0.105	0.000	77.8
Thinning Beta	2.082	1.84	0.27	1.056	0.123	0.000	72.0

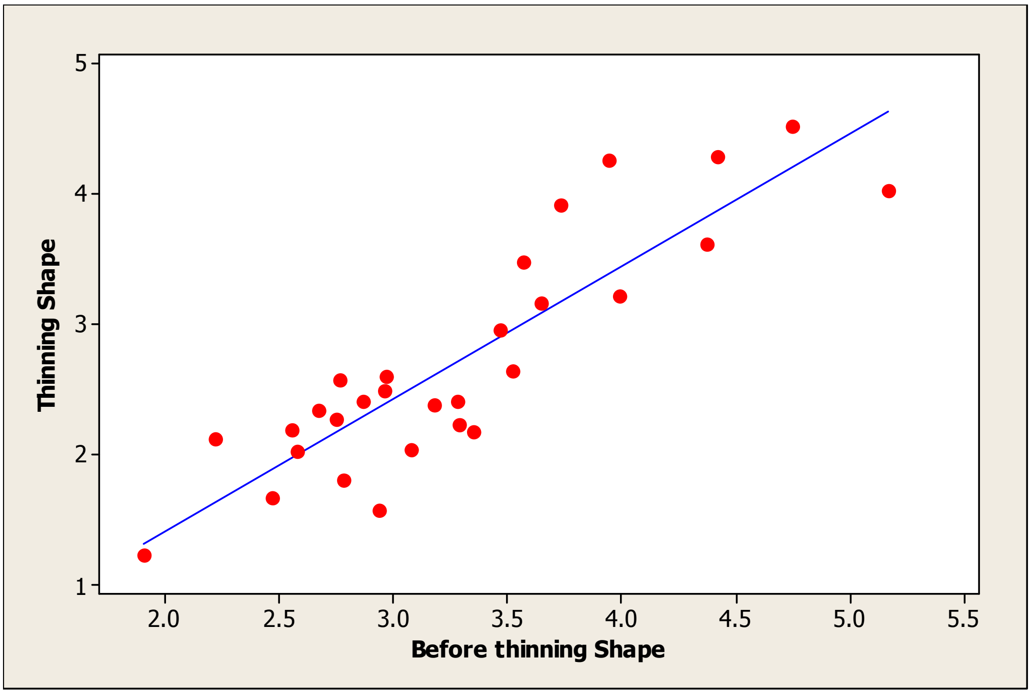


Figure 3.3: Before thinning shape parameter and thinning shape parameter relationship for Sitka spruce stands at first thinning

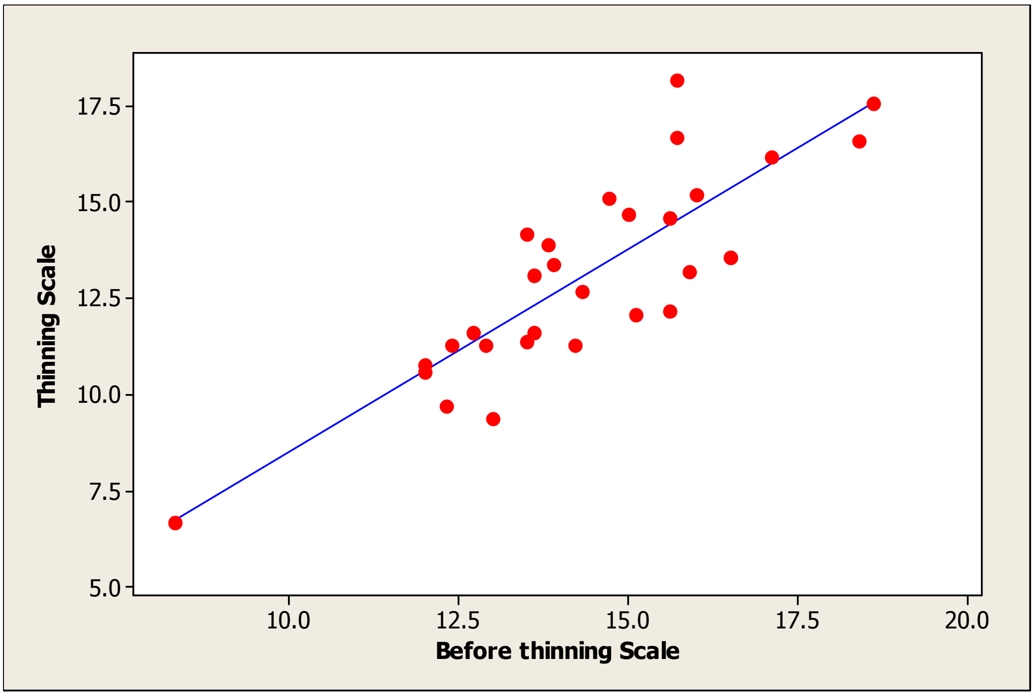


Figure 3.4: Before thinning scale parameter and thinning scale parameter relationship for Sitka spruce stands at first thinning

With these two regression equations, it is possible to estimate the parameters of the Weibull distribution function for a line and selection first thinning from the Weibull parameters of a before thinning distribution. Naturally, this is limited to the influences of the thinning type and other external factors experienced on the trial sites. However, it does allow the simulation of a thinning dbh distribution which is representative of a line and selection first thinning experienced on the trial sites when; either standing inventory data is available, or where the Weibull parameters can be estimated for in published forestry stand tables.

3.3.2 Before thinning and thinning parameters based on the British Forestry Commission stand tables

The Weibull distribution was found to fit the British Forestry Commission data significantly at an alpha level of 0.05 for all mean dbh levels (Anderson Darling test). The top height of the stand was estimated from the mean dbh / top height relationship identified in the British Forestry Commission yield tables. The parameters for the Weibull distribution for before thinning and thinning, along with the top height are detailed below in table 3.6.

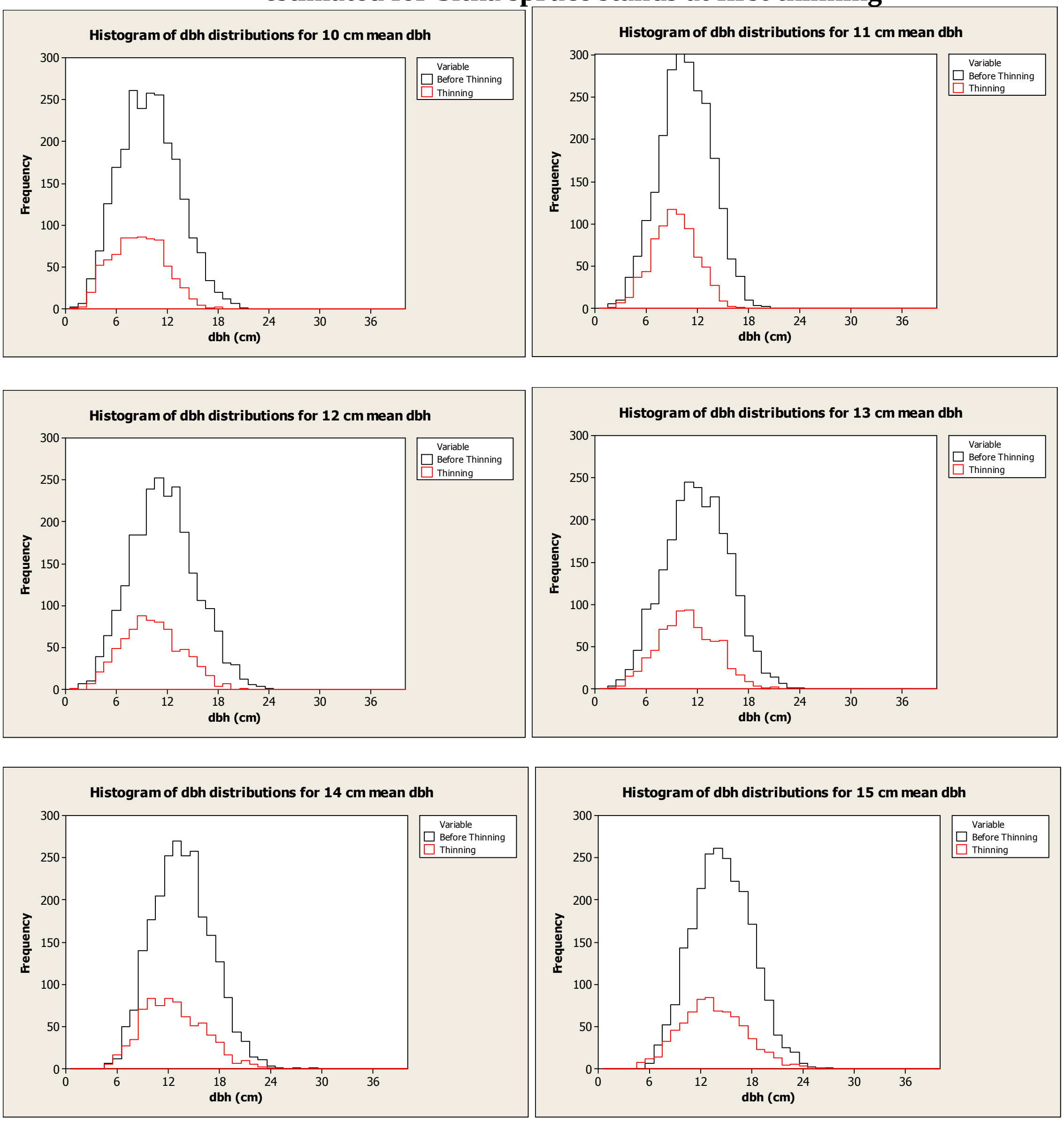
Table 3.6: Before thinning and thinning Weibull parameters for Sitka spruce stands at first thinning

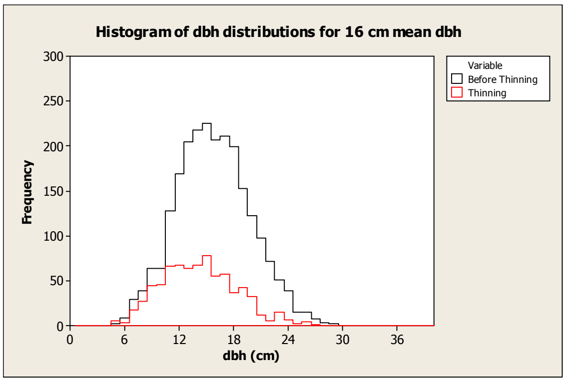
Main crop						Thinning using linear model	
Mean dbh	Top height	Threshold	Shape	Scale	P value	Shape	Scale
10	5.5	1	2.879	10.051	0.13	2.358	8.963
11	6.8	1	3.599	10.679	0.12	2.963	9.539
12	8	1	3.107	11.786	0.22	2.549	10.556
13	9.2	1	3.23	12.293	0.51	2.653	11.021
14	10.4	4	3.048	10.73	0.52	2.499	9.586
15	11.5	4	3.395	11.697	0.55	2.791	10.473
16	12.7	4	3.223	13.102	0.31	2.646	11.764
17	13.8	4	3.53	13.877	0.51	2.904	12.475
18	15	4	3.81	14.845	0.47	3.14	13.364
19	16.1	4	3.346	16.212	0.40	2.75	14.618
20	17.2	4	3.548	16.957	0.63	2.92	15.303
21	18.3	6.5	3.472	15.287	0.59	2.856	13.769
22	19.3	6.5	3.954	16.278	0.71	3.261	14.679

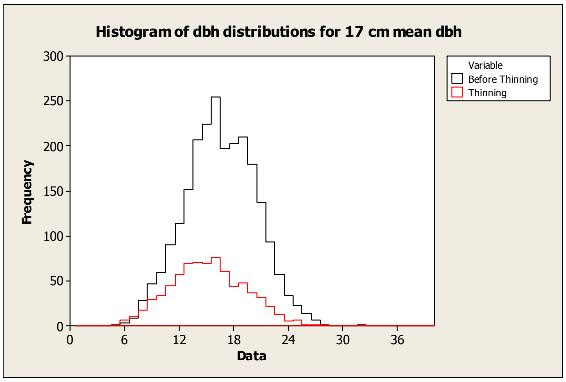
3.3.3 Simulation of thinning dbh distributions

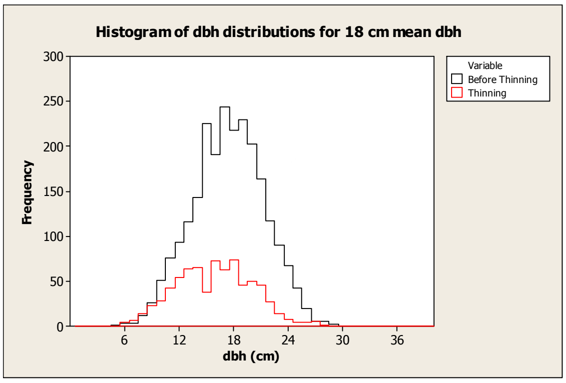
Monte Carlo simulation was used to create a before thinning and thinning distribution at each mean dbh level. The distributions are presented in a set of histograms in figure 3.5. It can be seen from the graphical display that in each case, the simulated thinning removes a larger proportion of the smaller stems, and leaves the majority of the larger stems standing. Importantly, this holds true at each level, and the thinning distribution does not predict stems which are outside of the bounds of the before thinning distribution. The mean of the thinning distribution is also showing to be lower than the before thinning, resulting in a higher mean dbh after thinning. All these characteristics are to be expected in a line and selection thinning.

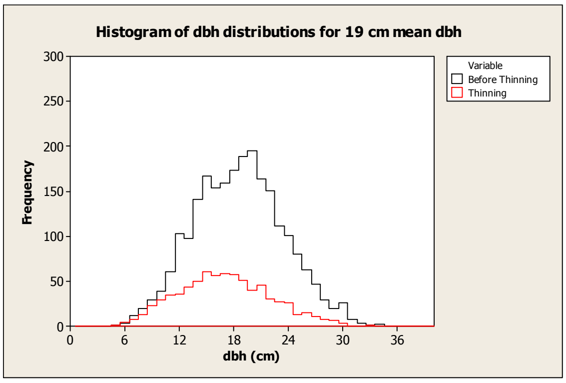
Figure 3.5: Dbh distributions from Monte Carlo simulations using the Weibull parameters estimated for Sitka spruce stands at first thinning

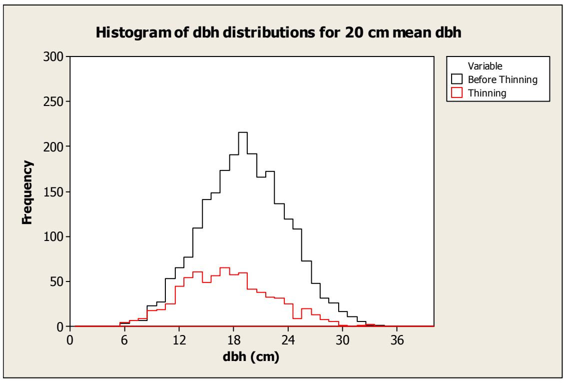


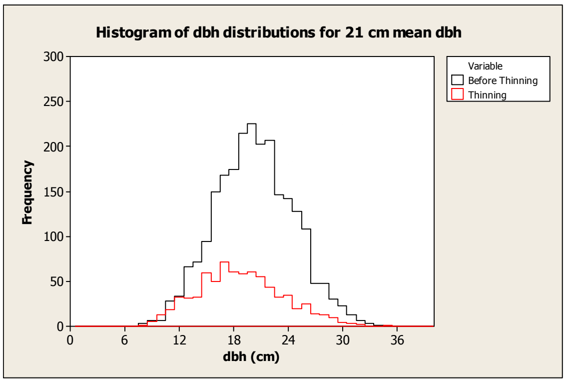

Histogram of dbh distributions for 16 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning

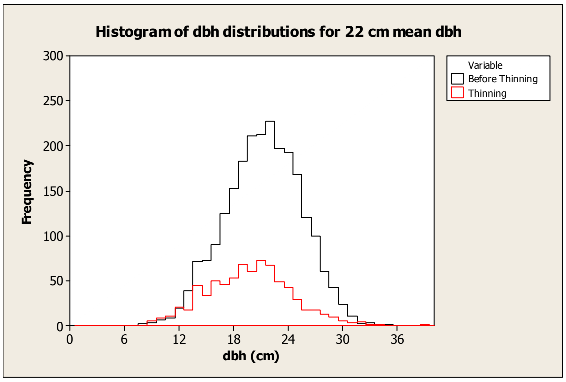

Histogram of dbh distributions for 17 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
Data
Variable
Before Thinning
Thinning


Histogram of dbh distributions for 18 cm mean dbh
Frequency
300
250
200
150
100
50
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning


Histogram of dbh distributions for 19 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning


Histogram of dbh distributions for 20 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning


Histogram of dbh distributions for 21 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning


Histogram of dbh distributions for 22 cm mean dbh
Frequency
300
250
200
150
100
50
0
0
6
12
18
24
30
36
dbh (cm)
Variable
Before Thinning
Thinning

3.3.4 Estimation of the volume from a thinning at each mean dbh level

The taper and dbh to height equations developed in chapter 2 were used, along with a biomass expansion factor developed by Levy *et al.* (2004), to estimate the different assortment volumes available in each individual tree from the thinning distributions simulated at each mean dbh level. The sum of these individual tree volumes is an estimate of the total volume available per hectare. Table 3.7 below details predicted total volumes per hectare, which includes the merchantable volume, large sawlog volume, small sawlog volume, pulp volume, total cut to length (CTL) log volume, and the whole tree volume. Also included is the count of each log assortment predicted.

Table 3.7: Predicted volumes for Sitka spruce stands at first thinning from the simulated datasets

			Cut to length (CTL) assortments							
Mean dbh	Merchantable vol. (m^3)	Full stem vol.	Large sawlog vol. (m^3)	No. large sawlog	Small sawlog vol. (m^3)	No. small sawlog	Pulp Vol. (m^3)	No. Pulp	Total CTL logs vol. (m^3)	Whole tree vol. (m^3)
10	10	13	0	0	0	0	3	83	3	20
11	14	17	0	0	0	0	7	218	7	25
12	20	24	0	0	1	18	13	358	14	36
13	25	29	0	0	2	35	17	485	19	43
14	39	44	0	0	9	139	24	658	33	64
15	50	54	0	0	15	214	28	787	43	78
16	61	66	0	0	22	309	31	863	54	93
17	74	80	0	0	33	461	36	1013	69	110
18	87	94	1	2	43	596	39	1114	82	126
19	109	116	8	29	55	723	41	1167	104	153
20	117	124	11	40	58	775	44	1262	112	161
21	146	154	20	73	74	996	48	1384	143	195
22	168	177	24	88	91	1218	48	1343	164	220

The CTL products, indicated by the shaded area are a component breakdown of the total CTL volume

The merchantable volume ranges from 10 m^3ha^{-1} to 168 m^3ha^{-1}. Interestingly the full stem only has an increased volume of 3 cubic metres at a mean dbh of 10 cm, to a maximum increase of 9 cubic metres at a mean dbh of 168 cm. The absolute values are small, but relatively it accounts for a 30% increase at a mean dbh of 10 cm. Even up to a mean dbh of 14 cm, the increase is 13%. However at the largest mean dbh of 22 cm, this only represents a 5% increase. Large sawlog only becomes available at 18 cm mean dbh, and at this level only produces 1 cubic metre. It could be suggested that large sawlog would not be viable to cut until 19 cm mean dbh, when there is 8 cubic metres available per hectare. At the upper end of a 22 cm mean dbh, 24 cubic metres per hectare of large sawlog available. The possibility of harvesting small sawlog begins at a mean dbh of 12 cm, but the quantities are small until 14 cm mean dbh, when 9 cubic metres are available per hectare. Pulp is available at every level, but again, the absolute volumes are small until about 14 cm mean dbh. Figure 3.6 graphically displays the volume predictions of the CTL assortments.

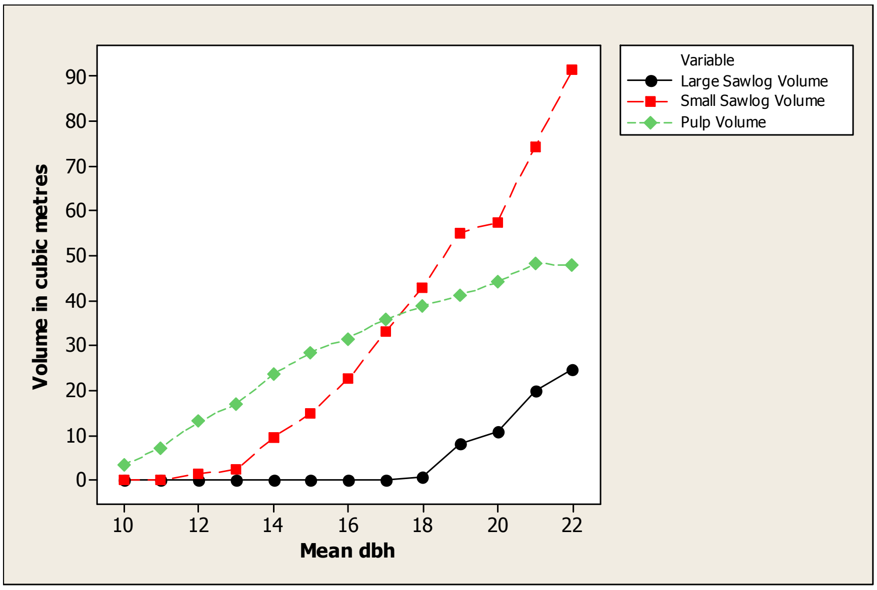


Figure 3.6: Predicted CTL volumes for Sitka spruce stands at first thinning from the simulated datasets

Whole tree volume ranges from 20 m^3 ha^{-1} to 220 m^3 ha^{-1}, which at the upper extreme of a mean dbh of 22 cm is a 34% increase over the total cut to length vol. At the lower extreme of a mean dbh of 10 cm, the increase is 560%. In figure 3.7 below, the whole tree volume, full stem volume, merchantable volume, and total cut to length volume at each mean dbh level are displayed. It can be seen from the graph that the merchantable volume, full stem volume, and total CTL volume are in close proximity to each other at every level. However, the absolute volume margin of higher volume attainable from the whole tree increases as the mean dbh level increases.

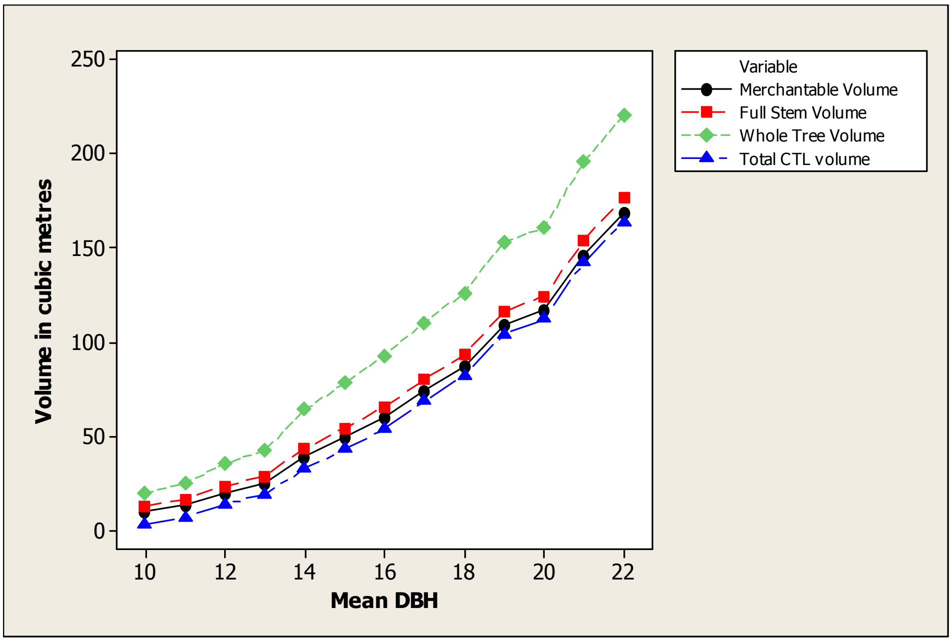


Figure 3.7: Predicted total volumes per hectare of Sitka spruce stands at first thinning from the simulated datasets

3.4 Concluding remarks

The distributions generated in this chapter are a representation of the trees removed in a line and selection first thinning. Using the stand parameters of top height and dominant dbh, as estimated from the distributions, these dbh values can be input into the taper and dbh/height models developed in chapter 2 to effectively predict a stem profile for each tree removed. As a whole, combining chapter 2 and chapter 3 of this dissertation, a tree level model of a stand has been developed at different stages of its development. This model has the ability to predict the dbh, height, taper, and volume of any assortment type, for each tree that will be thinned in the forest. This model can now be used with machine productivity studies to compare the production costs of different methods and systems of thinning at different levels of tree size (described by the parameter mean dbh). By modelling dbh distributions for a range of mean dbh levels (10 cm to 22 cm), and using the models developed in chapter 2, it was possible to predict volumes for each mean dbh level. The merchantable volume ranged from 10 m^2 ha^{-1} to 168 m^3 ha^{-1}, CTL volumes range from 3 m^3 ha^{-1} to 168 m^3 ha^{-1}, and whole tree volumes range from 20 m^3 ha^{-1} to 220 m^3 ha^{-1}. These results identify how the mean dbh of the stand at first thinning will greatly affect the capacity of the thinning operation to cover costs, and how at lower mean dbh levels, the adoption of whole tree harvest has the potential to recover 560% more volume than the CTL system.

Chapter 4: Machine rate and productivity of a harvester and a forwarder operating in a first thinning

4.1 Introduction

In Ireland, approximately 95% (Karjalainen et al., 2001) of harvesting machines use a cut to length method. This employs two machines, a harvester and a forwarder. The harvester fells, delimbs, and crosscuts the stems into specified lengths (assortments). The harvester then places them in small stacks in the forest. The forwarder extracts these logs to the roadside (Kent et al., 2011). The benefit of this system is the use of advanced computerized planning and control systems for optimal product and logistic efficiency. The system operation is focussed on quality, with low contamination from soil and losses of timber. It also has a reduced need for personnel on site than other systems (such as manual felling, whole tree extraction with processing at the roadside), making the system more viable for small plantations, as personnel cost is reduced (Harstela, 1999). In Europe, it has also been found that even in very favorable conditions for whole tree harvesting, the cut to length system is more cost effective unless utilizing the lop and top for energy (Harstela, 1999). Cut to length systems may also cause less residual stand damage than whole tree systems, as some whole tree systems skid intact trees to the forest roadside. In thinnings, the crop can suffer from the damage caused by the harvested trees hitting and rubbing off the remaining crop as they are pulled out of the stand (Forestry Commisson, 1997). However, this may only be the case when whole trees are extracted using a skidder, and may not be the case when using a terrain chipping system where the chip is forwarded to the roadside, much like a cut to length forwarder. On the other hand, cut to length systems may also provide a safer working environment than the manual harvesting associated with the whole tree harvesting system described in this dissertation, as the majority of work is done from the safety of highly protected cabs (Kellogg and Bettinger, 1994).

However, the equipment involved is capital intensive, requiring a continuous supply of work to cover ownership costs. In first thinnings, the economic margin is likely to be small due to the small tree sizes (Russell and Mortimer, 2005). Problems can occur on steep slopes, as the machines usually have to travel straight up and down steep terrain to maintain stability. When facing downhill, the harvesting head can often be obstructed from view by the wheels of the chassis. Under these conditions, operators often have to spend extra time maneuvering between felling and processing. Undergrowth and dense scrub can also affect visibility, and cause delays from damage caused to the chain, bar, and hydraulic hoses of the harvesting head (Richardson, 1989).

Jiroušek, Klva *et al*.(2007) trialled harvesting machines in Irish conditions and found that ground roughness, slope, stocking, number of log assortments processed, undergrowth density, and machine design are all factors affecting productivity. But it was found that tree size was the most significant. This is because harvesting machines are so efficient that they only take slightly more time to process a large stem, than a small stem. It is inevitable then that an increase in stem size will affect productivity (Ovaskainen, 2009). For the small tree sizes found in first thinnings, productivity can be expected to be in the region of 7.5 m^3 per productive machine hour (Sirén and Aaltio, 2003). Stampfer and Steinmüller (2001) describe how productivity models for forest harvesters contain three basic components: tree processing, locomotion, and delays. The tree processing component is a function of tree volume, harvesting intensity, stand density and silvicultural treatment. The locomotion component is a function of the terrain slope, stand density and soil bearing capacity.

Forwarder productivity has been found to be a function of distance, load volume and density of stacks (distribution) in the forest (Kellogg and Bettinger, 1994). Studies in Irish conditions have found that the productivity of forwarders in thinnings range from 5 to 14m^3 per productive machine hour, depending on these factors (Tiernan et al., 2004).

Productivity models are built from empirical data gathered from time studies of working machines (Eliasson et al., 1999, LeDoux and Huyler, 2001, Magagnotti and Spinelli, 2011, Howard and Coultish, 1993). Time study analysis uses only the productive time recorded in the field, quantified into productive machine hours (pmh). Delays or stoppages such as repairs, rest, maintenance, etc. are unproductive time and are not used to generate a productivity model (Johansson, 1997, Glode, 1999, Laitila et al., 2008, Gingras, 2005). This is because delays and stoppages such as repairs, rest, maintenance, telephone calls, or coffee breaks are infrequent and unpredictable. For example, the breakdown of a machine by its very nature is infrequent, and may not be captured even in a long time study of weeks, or even months. However, when a machine does break down it may be out of working order for a number of days or weeks. Therefore, when analysing the productivity of a machine using relatively short time studies, the productive time is used only (Spinelli and Visser, 2009). When relating productivity models to real world systems, the unproductive time is accounted for using utilisation rates. Utilisation rates are an estimation of the productive time as a percentage of the total time, scheduled machine hours (smh), and have been estimated from long time historical data of machines (Spinelli and Visser, 2009). A benefit of using allowances is that is if the allowance is thought to be too low or too high they can be adjusted, and the results recalculated. This may be the case if a machine is operating in rough site conditions, the operator use is hard on the machine, the operator needs more rest due to environmental conditions, or a machine age/condition is causing more breakdowns (Kent et al., 2011).

The aim of this chapter is to develop harvester and forwarder productivity equations that represent the operations that took place on the trial sites. The productivity models are to be compatible with the taper and dbh to height models developed in chapter 2, and the data produced in chapter 3. That is, the productivity models' independent variables will be linked to the dependant variables from the models developed in chapter 2.

Many publications on harvesting productivities relate time consumption to standing tree volume or dbh (Evanson and McConchie, 1996), (Spinelli et al., 2002). In this study, a meaningful relationship between the output volume from a harvester and its productivity was investigated, as this would allow for the productivity model to be directly compatible with the output from the taper and height models developed in chapter 2.

4.2 Material and methods

4.2.1 Harvester Model Data Collection

A Silvatec 120KW harvester was trialed on 5 sites during the Forest energy programme. However, only 1 site had the data collected in a sufficient manner that the operation could be parameterized. This site was a 2.8 hectare plot in Abbyfeale, Co. Limerick. A line a selection thinning was carried out. One row in seven was removed for the line thinning, and the selection thinning carried out between the lines. The thinning removed 40% of the stems, 14% being from the extraction rack, the remaining 26% from the selection thinning. The stems were delimbed by the harvester head and cut into sawlog, pallet, and pulp assortments. The assortments were accumulated separately in small stacks perpendicular to the line. The tops and branch material were placed under the machine as a brash mat. Table 4.1 details the site characteristics.

Table 4.1: Site characteristics for the harvester study

Site	Species	Plot Area	Age	Stocking	Mean dbh	Top Height	Yield Class
		ha	year	stems/ha	cm	m	m^3/ha/yr
Abbeyfeale	Sitka spruce	2.8	20	2134	17	14.0	24

A continuous time study was carried out using a Husky field computer running the Siworks3 time study software. The time study treated each tree as a productive cycle. The Siwork3 software records time in centiminutes (centimins). One centimin is equivalent to 100th of a minute. Centimins are commonly used in time studies because of their ease of their use in arithmetic. Each observation was divided into the following elements:

- **Move:** Starts when the harvester moves to travel a distance. Ends when the harvester stops again.
- **Select:** Starts when the operator is ready to fell the next tree. Ends when the harvester head grabs the tree.
- **Fell:** Starts when the harvester head grabs onto a tree. Ends when the head pulls the tree butt away from the stump.
- **Down:** Starts when the head pulls the tree butt away from the stump. Ends when the rollers on the head start to move for processing.
- **Processing:** Starts when the rollers on the head start to move for processing . Ends when the last product length is dropped from the head.
- **Tops:** Starts when the last product length is dropped from the head. Ends when the tops are placed on the ground.
- **Delays/Unproductive:** Any time which does not apply to the above elements.

To evaluate the relationship between tree size and productivity, a count of the logs and their assortment type was recorded for every machine cycle. After the harvesting operation was completed on the site, a number of logs of each assortment were measured with a logger's tape and callipers. This was done in order to estimate a mean volume per assortment. As many logs as possible were measured in the available time on the site. Logs were measured throughout the site in order to get an even sample spread. Table 4.2 displays the assortment dimension statistics for the trial site.

Table 4.2: Sample logs measured on the site to estimate the mean volume per assortment

Statistic	Pulp			Pallet			Sawlog		
n	77			61			25		
	Length (cm)	Mid Diameter (cm)	Volume (m3)	Length (cm)	Mid Diameter (cm)	Volume (m3)	Length (cm)	Mid Diameter (cm)	Volume (m3)
Mean	295	13	0.038	251	18	0.066	490	22	0.193
Standard Deviation	15	3	0.017	3	3	0.002	11	1	0.023
Min	243	6	0.008	241	13	0.033	449	20	0.153
Max	334	22	0.111	258	26	0.132	519	26	0.266

The mean volumes and the count of the assortments per tree gave an estimate of the volume harvested in each tree. The data was analysed with regression techniques in the Minitab 16 statistical software package.

The machine rate calculation method by Miyata *et al.* (1980) was used to estimate the cost of the harvester per productive and scheduled machine hour. This method has been used in many productivity reports since its publication (LeDoux and Huyler, 2001, Behjou et al., 2009), and very recently by Magagnotti and Spinelli (2011). The machine rate assumptions for the harvester are detailed in table 4.3.

Table 4.3: Machine rate calculation assumptions for the harvester

Rate	Unit	Amount
Initial Investment	Euro	300000[a]
Machine Power	kw	120[a]
Salvage value %	%	20[b]
Salvage Value	Euro	60000
Economic Life	years	6[b]
Scheduled Operating hours	hrs/year	2000
Utilisation Percentage	%	70[c]
Productive Machine Hours	hrs/year	1400
Interest Rate	%	8.5[b]
Insurance and tax rate	%	4[b]
Repair and Maintenance	% of depreciation	100[b]
Depreciation	Euro/year	40000
Average Yearly Investment	Euro/year	200000
Interest	Euro/year	17000
Insurance and Tax	Euro/year	8000
Maintenance and Repair	Euro/pmh	28.6
Fuel Consumption Rate		0.06[b]
Cost of litre of fuel		0.92[b]
Fuel	Euro/pmh	6.8
Lubrication Consumption Rate		0.35[b]
Lubrication	Euro/pmh	2.4
Labour	Euro/pmh	22.6[b]
Benefits	Euro/pmh	5.6[b]
Overheads %	%	5[b]
Operating Profit %	%	9[b]
Ownership cost per SMH	Euro/smh	32.5
Ownership cost per PMH	Euro/pmh	46.4
Operating cost per PMH	Euro/pmh	66.0
Operating cost per SMH	Euro/smh	46.2
Overheads per SMH	Euro/smh	3.9
Operating Profit Per SMH	Euro/smh	7.4
Total Rate per SMH	Euro/smh	90.1
Total Rate per PMH	Euro/pmh	128.7

Sources: [a] Machine owner, [b] (Murphy et al., 2010), [c] (Kent et al., 2011)

4.2.2 Forwarder model data collection

Shortly after harvesting, the assortments were extracted to the forest roadside with a Valmet 90KW forwarder. The assortments were placed in large stacks perpendicular to the roadside. In order to get a sufficient sample size, the forwarder was trialled on a total of three sites, including the Abbyfeale site used for the harvester model. All sites were prescribed the same thinning regime as the harvester trial site, and are described in table 4.4 below.

Table 4.4: Site characteristics for the forwarder study

Site	Location	Species Composition	Plot Area	Age	Stocking	Mean dbh	Top Height	Yield Class
			ha	year	stems/ha	cm	m	m^3/ha/yr
Abbeyfeale	52°25'6.46"N , 9°14'23.32"W	Sitka spruce	2.8	20	2134	17	14.0	24
Ballybofey	54°49'54.36"N, 7°45'39.02"W	Sitka spruce/larch	12.4	13	2537	14	11.0	24
Woodberry	53°17'47.74"N, 8°24'26.03"W	Sitka spruce	13.6	17	2327	14	11.9	24

The time study of the forwarder was carried out using a stopwatch, recording productive time only. A cycle was defined as the extraction and stacking of a forwarder bunk of timber to the forest roadside. Each cycle was divided into the following elements:

- **Drive Empty:** Starts when the forwarder begins the journey into the forest. Ends when the forwarder stops to pick up the first log of the load.
- **Loading:** Starts when the machine stops to pick up the first log. Ends when the machine loads the last log and starts to move back towards the staking area.
- **Drive Full:** Starts when the machine begins its journey back to the roadside. Ends when the machine stops to unload at the roadside.
- **Unloading:** Starts when the machine stops to unload the logs at the roadside. Stops when the last log is unloaded and the machine is ready to move back into the forest.

As per the harvester model, a sample of logs was measured on the forest floor to estimate the mean volume of each assortment. A count of the logs and their assortment type was recorded for each forwarder bunk load, and from this, an estimate of each load volume calculated. As the Ballybofey site comprised of an intimate mixture of Sitka spruce and larch, it was necessary to identify if the larch had any effect on the productivity. It was found that the mean assortment volumes between the two species did not differ significantly at an alpha level of 0.01 when tested with an ANOVA. On the Woodberry site, an amount of stake wood was also produced. Table 4.5 details the mean assortment volume on each site.

Table 4.5: Sample logs measured on the forwarder study sites to estimate the mean assortment volume

Site	Pulp		Pallet		Sawlog		Stake	
	n	Volume (m3)	N	Volume (m3)	n	Volume (m3)	n	Volume (m3)
Abbyfeale	77	0.383	61	0.067	25	0.193	-	-
Ballybofey	134	0.029	-	-	-	-	-	-
Woodberry	169	0.032	35	0.050	-	-	224	0.013

Distance is considered a major factor affecting timber extraction productivity (Jackson et al., 1990, Sirén and Aaltio, 2003, Behjou et al., 2008). Alongside the cycle times and piece count for each load, the distance was also recorded in metres with a walk tax. The distance variable was measured over three separate elements; the distance travelled when driving empty, the distance travelled when loading, and the distance travelled when driving full. The sum of these distances was considered the total distance travelled in a cycle. As per Tiernan *et al*. (2004), the average extraction distance per cycle was used in the analysis, and was estimated as half of the total cycle distance.

The machine rate analysis was carried out with the same method as the harvester machine. The assumptions are detailed in table 4.6.

Table 4.6: Machine rate calculation assumptions for the forwarder

Rate	Unit	Amount
Initial Investment	Euro	210000[a]
Machine Power	kw	90[a]
Salvage value %	%	20[b]
Salvage Value	Euro	42000
Economic Life	years	6[b]
Scheduled Operating hours	hrs/year	2000[b]
Utilisation Percentage	%	70[c]
Productive Machine Hours	hrs/year	1400
Interest Rate	%	8.5[b]
Insurance and tax rate	%	4[b]
Repair and Maintenance	% of depreciation	100[b]
Depreciation	Euro/year	28000
Average Yearly Investment	Euro/year	140000
Interest	Euro/year	11900
Insurance and Tax	Euro/year	5600
Maintenance and Repair	Euro/pmh	20
Fuel Consumption Rate		0.06
Cost of litre of fuel		0.92[b]
Fuel	Euro/pmh	5.1
Lubrication Consumption Rate		0.35[b]
Lubrication	Euro/pmh	1.8
Labour	Euro/pmh	22.6[b]
Benefits	Euro/pmh	5.6[b]
Overheads %	%	5[b]
Operating Profit %	%	9[b]
Ownership cost per SMH	Euro/smh	22.8
Ownership cost per PMH	Euro/pmh	32.5
Operating cost per PMH	Euro/pmh	55.1
Operating cost per SMH	Euro/smh	38.6
Overheads per SMH	Euro/smh	3.1
Operating Profit Per SMH	Euro/smh	5.8
Total Rate per SMH	Euro/smh	70.2
Total Rate per PMH	Euro/pmh	100.3

Sources: [a] Machine owner, [b] (Murphy et al., 2010), [c] (Kent et al., 2011)

4.3 RESULTS AND DISCUSSION:

4.3.1 Harvester Time Consumption Analysis.

The study duration of the harvester lasted for 15537 centimins (155 mins), including delays. The study captured 182 cycles of the harvester. The mean productive time per cycle was 69.1 centimins, with a minimum of 27.0, and a maximum of 127.0 centimins. Figure 4.1 displays the percentages of time consumption for each element. An evaluation of the elements found that 26.1% of the time was consumed processing the stems, which included the delimbing and cross-cutting of the stem into specified assortment dimensions. The selection of the trees took 25.2% of the total time, where the operator was deciding which tree to thin out, and was moving the boom into position around the remaining trees. Felling consumed 9.9%, and pulling the tree down into a horizontal position for processing took 12.1% of the time. The tops time element included the positioning of the top onto the ground for use as a brash mat. This element also often included the repositioning of pieces of brash to improve the brash mat, and consumed 14.1% of the time. The delay element, which comprised of machine interruptions and personal delays, totalled to 11.5%. The smallest time element from the results was the move time, which was 1.1% of the total time, and was erratic in its occurrence. Figure 4.2 shows the time series graph for the delay element, which illustrates the infrequent occurrence of the moving of the machine. During the time study data collection, the harvester moved slowly through the stand while performing operations tied to other elements, in particular the tops element and the processing element. These other elements were given priority over the move component as they were more closely related to the output of volume.

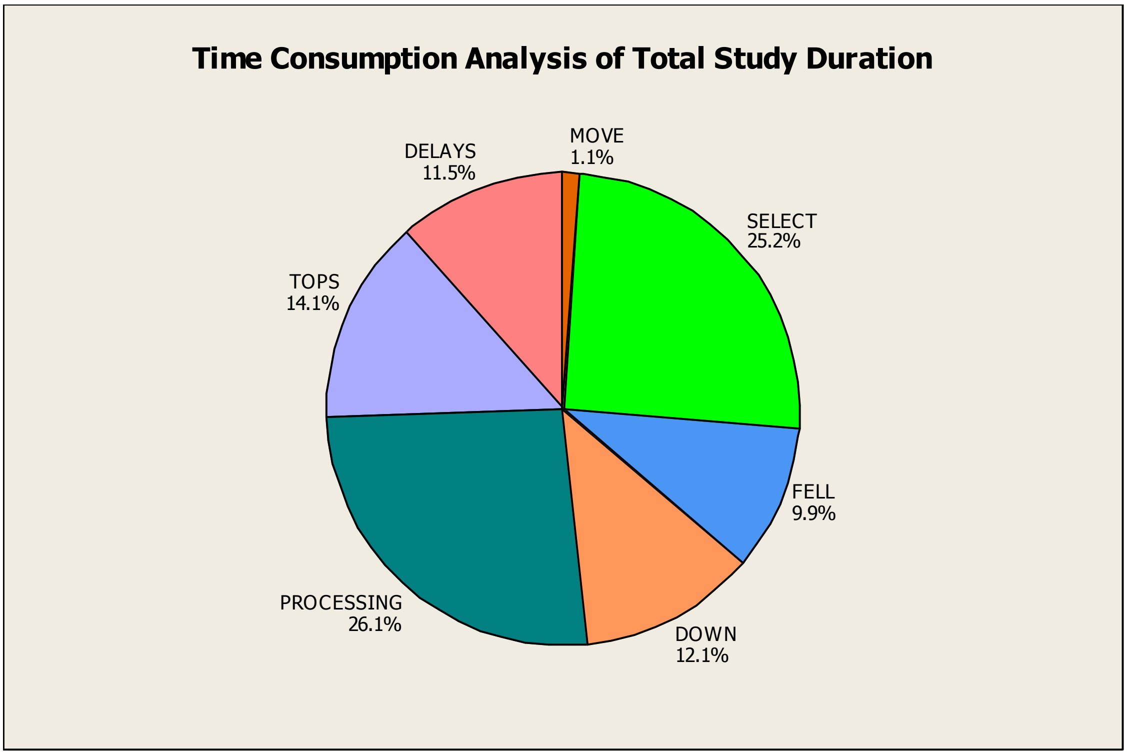


Figure 4.1: Percentages of total cycle time, including delays, of the harvester cycle time elements

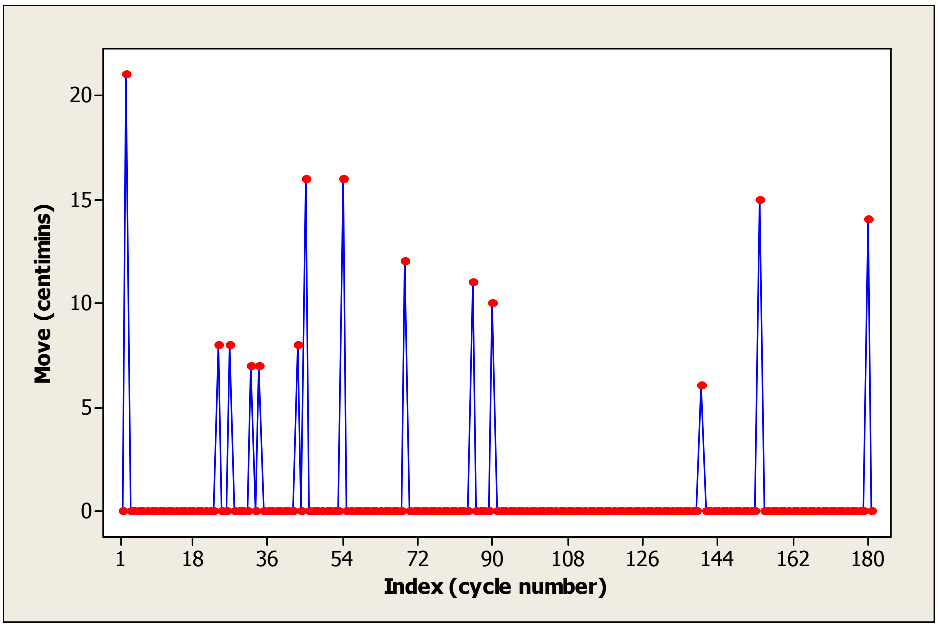


Figure 4.2: Series plot of the move element in the harvester study

4.3.2 Harvester model development.

A time series analysis of the aggregate effective cycle time shows that the harvester system was relatively stable over the study period. Figure 4.3 displays the time series graph.

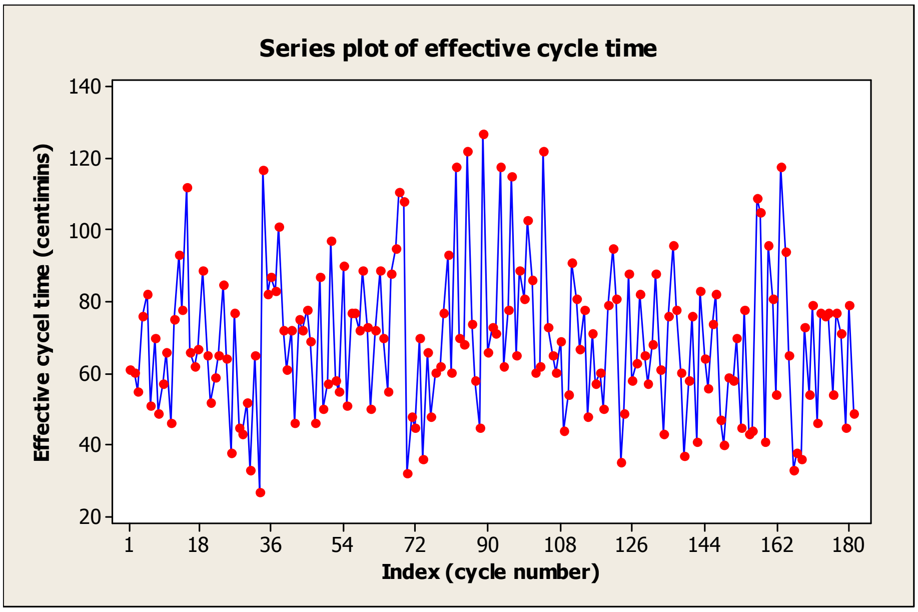


Figure 4.3: Time series plot of the harvester time study

The model was developed using least squares regression in the Minitab 16 statistical program. The model was developed so that: $Cycle\ Time = f(Harvested\ Vol)$. Initially, parameters were included in the model to account for the number of logs cut from each tree, however this only marginally increase the R^2 adjusted statistic, and was considered an over parameterisation.

A quadratic term was included in the model so that:

$$Harv_{t_i} = \beta_0 + \beta_1 H_{v_i} + \beta_2 {H_{v_i}}^2$$

Where:

$Harv_{t_i}$ = Aggregated effective cycle time (productive time) of the harvester for the *ith* tree (centimins)

H_{v_i} = Harvested volume of the *ith* tree (m^3)

β_0 to β_3 = parameters to be estimated from the regression. β_0 being the y intercept.

The residual plots showed that the model did benefit from the quadratic term, particularly fitting to the larger trees in the dataset. The results from the regression gave an overall significant relationship between the independent and dependant variables with a P value of <0.0001. However, the coefficient of determination is quite low at 34.22%, and the R^2 adjusted at 33.48%. Examining the residuals, as illustrated in figure 4.4, the low R^2 value is due to the averaging of the assortment volumes. If an individual measurement of the volume of the logs harvested from each tree had been taken, the data would be spread out more along the model line. In the scatter plots presented, the points are clustered into 7 main groups. In each of these groups, the same combination of assortments was harvested per tree. The data higher up on the Y axis of each cluster are likely to be farther to the right on the X axis and closer to the model line, and likewise, the data lower down on the Y axis for each cluster is most likely farther to the left on the X axis, and closer to the model line. Therefore, it's quite possible that the model can account for more variation than is reported by the R^2 statistic. It is important to note that the model can only be used within the range of independent variables from which it has been developed, that is from 0.038 m^3 to 0.270 m^3. To extrapolate beyond these limits will result in major errors, as the quadratic equation used to describe the relationship, by its very nature, will return values that will become infinitely large as the model reaches an asymptote.

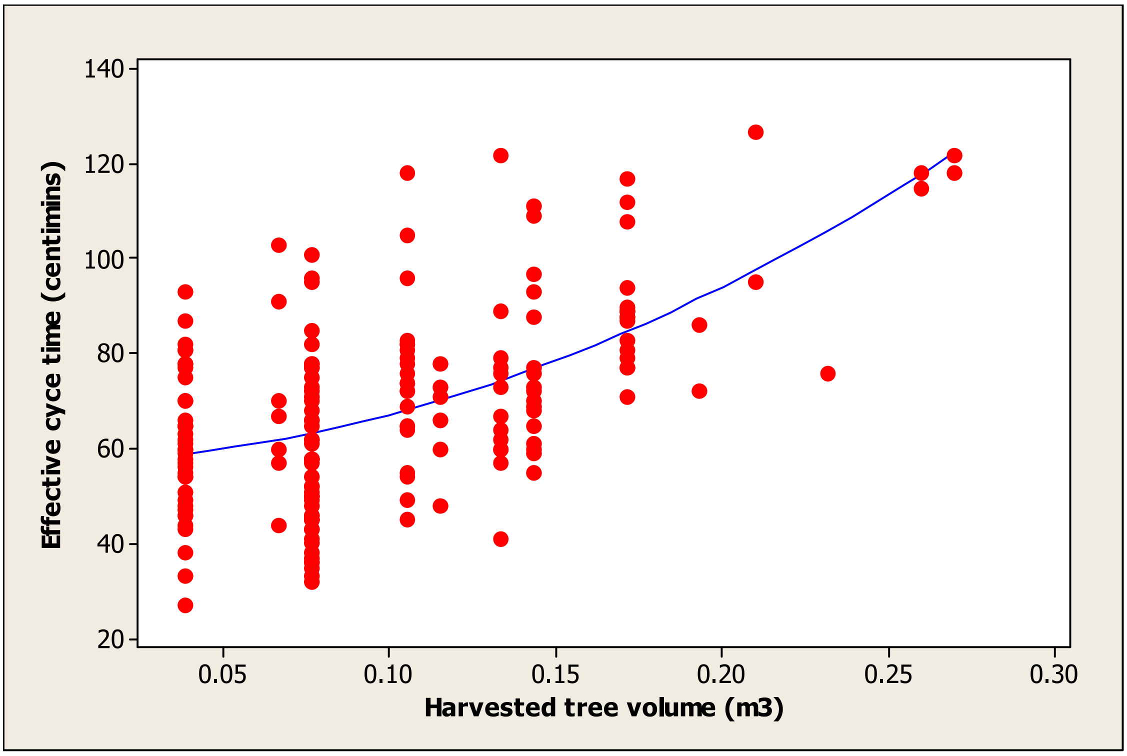


Figure 4.4: Scatter plot of the effective cycle time versus the harvested tree volume, included is the plot of the harvester model describing the relationship

The fit statistics for the quadratic model indicate that the residuals are normally distributed. The residuals were tested with an Anderson Darling probability of fit, and gave a P value of 0.421. The coefficients of the regression equation are given in table 4.7.

Table 4.7: Parameter estimates for the harvester model

Term	Coefficient	Standard Error	P value
Constant	56.429	4.92	0.000
Hv	24.473	87.631	0.780
Hv^2	814.489	340.925	0.018

From the table of coefficients, it can be seen that the harvested volume variable was not significant. However, the quadratic harvested volume term has shown to be significantly different from zero. According to Bonate (2006), if a quadratic term is significant in a regression model, the linear variable terms should also be retained. Therefore, the harvested volume variable remains in the model.

A model for the prediction of the cycle time of the harvester as experienced in the trial is given as:

$$Harv_{t_i} = 56.429 + 24.473H_{v_i} + 814.489{H_{v_i}}^2$$

To predict the harvesting cost per cubic metre according to the harvested tree volume and number of pieces, the model can be extended to add the harvester machine rate of €128.7 per productive machine hour. The utilization percentage, which accounts for delays, is accounted for in the productive hour cost.

The average cost of harvesting per cubic metre can be estimated from:

$$H_{cost/m^3} = \frac{128.7}{H_v/\left[(56.429 + 24.473H_v + 814.489{H_v}^2)/6000\right]}$$

Where:

H_{cost/m^3} = Harvester cost per cubic metre (€)

The dbh distributions developed in chapter 3 were used to generate data to input into the harvester model. This simulated the productivity of the harvester at different levels of mean dbh. For each dbh generated, the dbh/height model and taper model were applied to calculate the harvestable volume of the tree (the assortment specifications were as per table 3.4). The time to harvest each tree was estimated from the model, and the time per cubic metre calculated. The number of stems removed per hectare in the simulations was 751, as described in chapter 3. Figure 4.5 below shows the delay free time to harvest a hectare at each mean dbh level. The results show that the time ranges from 7 hours at a mean dbh level of 10 cm, to 11 hours at a mean dbh level of 20 cm. The results concur with the harvester model that harvesting time increases as tree size increases.

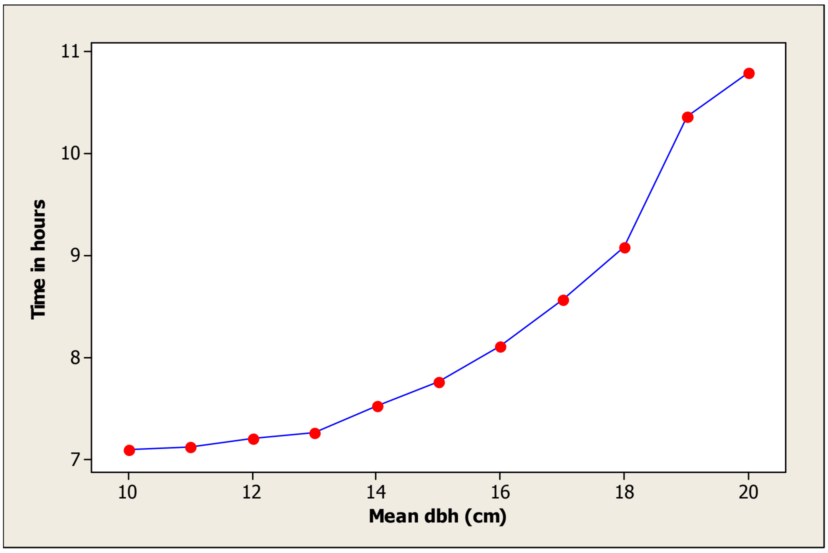


Figure 4.5: Predicted delay free harvesting time per hectare of the harvester in Sitka spruce plantations at first thinning

Figure 4.6 below illustrates the productivity of the harvester at each mean dbh level. The productivity results range from 0.5 m^3 per hour at a mean dbh level of 10cm, to 10.4 m^3 per hour at a mean dbh level of 20 cm. The productivity of the harvester is very low at the smaller mean dbh levels because many of the trees are so small that no assortments can be cut. In these cases, the model predicts a mean harvesting time of 56.4 centimins, (approx 31 seconds) which is the y-axis intercept in the model's equation. This means that for every tree which cannot be processed into logs, the harvester will spend an average of 31 seconds felling and discarding the tree. This is where this technique of productivity estimation is beneficial, as predicting productivity on the basis of standing volume estimates may not capture the affect of the small non merchantable trees. It would be incorrect to give the non merchantable trees a zero harvest time, as the thinning operation is primarily a silvicultural operation, and so a prescribed number of trees must be removed. For instance, the results show that at a mean dbh level of 10 cm, only 11.1% of the trees harvested were of sufficient dimensions to be processed into any assortments, 89% of the trees were of no commercial value as CTL products. Nurminen *et al.* (2006b) studied the productivity of a harvester machine working in conifer plantations during thinnings, and found the harvester productivity ranged from approx. 3 m^3 per hour to 16 m^3 per hour, depending on tree size. Nurminen's results are similar in scale and trend to the predicted harvester productivity illustrated in Figure 4.6, corroborating the results found in this study.

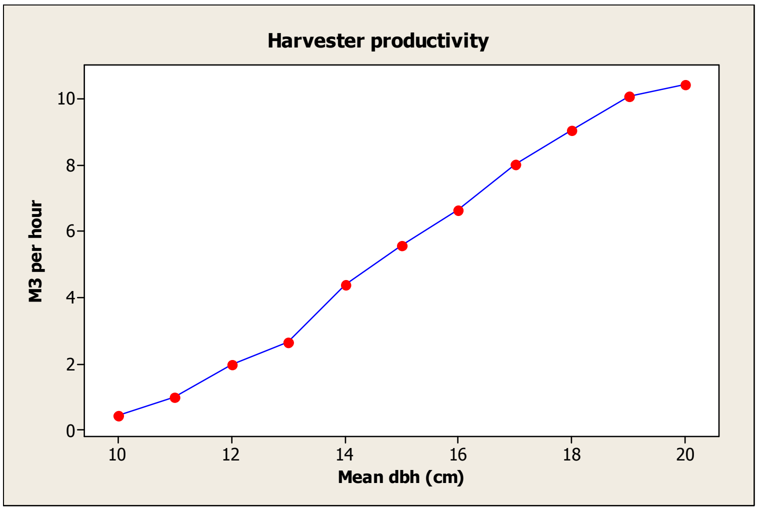


Figure 4.6: Predicted harvester productivity in Sitka spruce plantations at first thinning

Figure 4.7 shows the cost per m^3 produced by the harvester according to the stand mean dbh. At a mean dbh of 10 cm, the cost of production is very high at €285 per m^3. Again, this is a result of the large proportion of non merchantable trees at this dbh level. As mean dbh increases, it is only at around the 14 cm mark that harvesting costs become acceptable. At 14 cm dbh, the cost per m^3 of production from the harvester is estimated as being €29. From this point, the change is more gradual as mean dbh increases, at 17 cm mean dbh the cost of production is €16 / m^3, at 20cm mean dbh the cost is €12 / m^3. Table 4.8 details all the results.

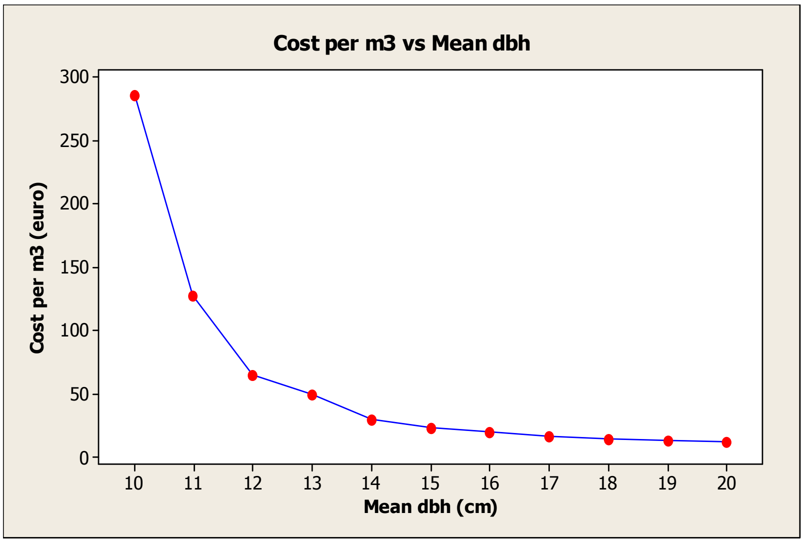


Figure 4.7: Predicted cost of production for the harvester in Sitka spruce plantations at first thinning

Table 4.8: Simulation results for the harvester in Sitka spruce plantations at first thinning

Mean dbh (cm)	Delay free harvesting time per hectare (hours)	m^3 per hour	Cost per m^3
10	7.1	0.5	285.2
11	7.1	1.0	128.0
12	7.2	2.0	65.3
13	7.3	2.6	49.0
14	7.5	4.4	29.5
15	7.8	5.6	23.2
16	8.1	6.6	19.4
17	8.6	8.0	16.0
18	9.1	9.1	14.2
19	10.4	10.1	12.8
20	10.8	10.4	12.4

4.3.3 Forwarder Time Consumption Analysis

A series plot of the data points show that the data has distinct groups, as shown in figure 4.8. This caused concerns that unmeasured site variables may impact on the study results. Differences in the average extraction distance, load volume, and piece count can be accounted for in the model, however, unmeasured factors of the differences between sites may cause under-parameterization. To investigate this, a general linear model (GLM) was used for an analysis of covariates between the sites. The null hypothesis tested was that the productive cycle time differences between the sites equaled zero, when adjusted for the covariates of average distance, load volume, and piece count.

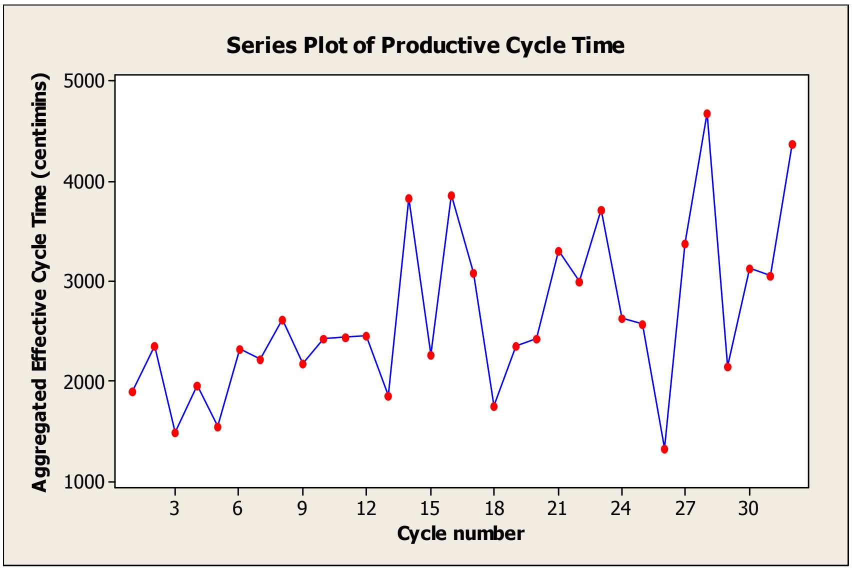


Figure 4.8: Series plot of the forwarder time study

The analysis of covariance (ANCOVA) in the GLM results indicate that the differences between sites are significantly different at an alpha level of 0.05 when adjusted for the covariates. This suggests that variables inherent to each site that were not measured have an impact on the results. The GLM ANCOVA results are detailed in table 4.9.

Table 4.9: General linear model analysis of covariates for the forwarder sites

Source	DF	Seq SS	Adj SS	P
Average Distance	1	11969406	12296860	0.000
No of Pieces	1	1947651	4008035	0.000
Total Load Vol	1	4221649	2050346	0.000
Site	2	816526	816526	0.009
Error	26	1893111	1893111	
Total	31	20848343		

As a result, it was decided that the data for the forwarding model be confined to one site. Site 5 was chosen as it had the most data points collected in the study. The time study duration on site 5 lasted 56968 centimins (5.7 hours). A total of 19 cycles were captured, the mean cycle time was 2998 centmins, with a minimum of 1327, and a maximum of 4685 centimins. The mean average distance of a cycle was 278 metres, the minimum was 58 metres, and the maximum was 720 metres. Figure 4.9 illustrates the percentages of time consumption for each element in the forwarder cycle. It was found that the drive empty element consumed 13.4% of the effective time, which involved the forwarder driving from the stacking area to the processed log bunches in the forest. The loading element, which consisted of filling the forwarder bunk and moving between the log bunches in the forest, took 68.2 % of the time. The drive full element consumed 6.7% of the time, which involved the driving of the forwarder back to the stacking area at the forest roadside. The unloading of the logs from the forwarder bunk into stacks at the forest roadside consumed 11.7% of the time. Interestingly, the drive full element time consumption is lower than that of the drive full time element. Convention thought suggests that the machine should travel faster when empty. However, it was observed that, in general, the forwarder driver made decisions about extraction on the journey into the forest; identifying the log bunches and best extraction routes. The forwarder would slow down during its journey as the driver observed the site and made these decisions. Once the forwarder bunk was full, the forwarder operator would drive directly back to the stacking area, without the need to make any other decisions.

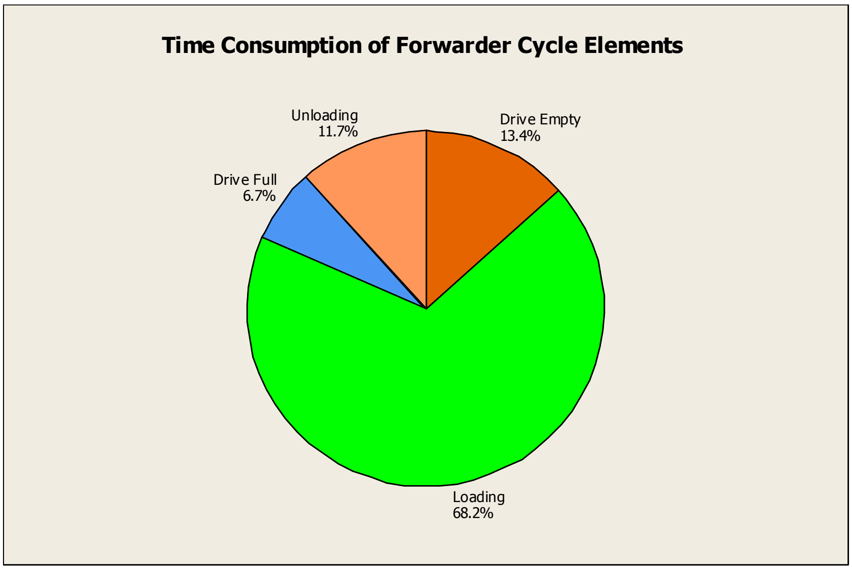


Figure 4.9: Percentages of the forwarder cycle time elements observed during the time study

4.3.4 Forwarder Model Development:

The forwarder model was fit to the data using ordinary less squares regression in the Minitab 16 statistical package. The model was developed to be integrated with the taper and height models in chapter 2, so that:

$$Cycle\ Time = f(Distance, Load\ Volume, No.of\ Pieces).$$

The distance and load volume are independent variables that are set by site factors and machine configuration respectively. The number of pieces independent variable will be a function of the taper and height model in chapter 2. The linear regression equation was estimated in the form:

$$Forw_t = \beta_0 + \beta_1 Dist + \beta_2 Load_v + \beta_3 Piece_c$$

Where:

$Forw_t$ = Forwarder productive cycle time (centimins)

$Dist$ = Average extraction distance (m)

$Load_v$ = Load volume (m^3)

$Piece_c$ = Piece count (number of logs in the load).

β_0 *to* β_3 = Parameters to be estimated from the regression. β_0 being the y intercept.

The regression has shown to be statistically significant at an alpha level of 0.05. The P value for the overall regression is <0.0001 The R^2 value is relatively high at 90.04%. The R^2 adjusted is 88.0%. The fit statistics are given in table 4.10. The model did benefit greatly with the inclusion of the number of pieces variable. If compared to a regression analysis where this variable was left out, the R^2 drops to 65%, and the R^2 adjusted to 61%. Initially, a term was included for the interaction between the load volume and the number of pieces. This interaction term was found to be insignificant in the regression and was removed. This raised concerns, as it can be assumed that the number of pieces will affect the load volume. Although it turned out to be insignificant in this analysis, the interaction will be accounted for by the taper and height models from chapter 2. That is, the number of pieces required to fill the forwarder bunk is a function of the log volumes that are cut from the stem, and the size of the forwarder bunk.

Table 4.10: Parameter estimates for the forwarder model

Term	Coef	SE Coef	P
Constant	850.48	298.90	0.012
Average Distance	4.91	0.44	0.000
Load Volume	-224.37	70.02	0.006
No. of pieces	12.33	2.04	0.000

The analysis of the residuals from the equation tested the residuals for normality. An Anderson Darling test has given a P value of 0.958 for the normal distribution fit to the data, meaning that the residuals are normally distributed. A model for forwarding cut to length roundwood as experienced in the trial is given as:

$$Forw_t = 850.48 + 4.91Dist - 224.37Load_v + 12.33Piece_c$$

The prediction of the average cost per cubic metre can be estimated, like the harvester model, by adding the forwarder machine rate per productive machine hour of €100.3. The equation is given below.

$$Forw_{cost/m^3} = \frac{100.3}{Load_v/[(850.48 + 4.91Dist - 224.37Load_v + 12.33Piece_c)/6000]}$$

Where:

$Forw_{cost/m^3}$ = Average forwarding cost per cubic metre (€)

Similar to the harvester, the model was used with the dbh distributions developed in chapter 3, and the taper model and dbh/height model, to simulate the productivity of the forwarder at different mean dbh levels and extraction distances. The load capacity of the forwarder was set as the mean load volume observed during the trial, which was 4.4 cubic metres solid volume. The number of pieces per load was estimated by dividing the load capacity volume by the mean log volume as predicted by the taper equation. Figure 4.10 below shows the cycle time per load from the simulations. It is predicted that the forwarding cycle time will vary between 10 mins and 64 mins, depending on the mean dbh level, and the average extraction distance. Tiernan *et al*. (2004) observed that cycle times for a forwarder with a 4 m^3 capacity were in the region of 20 mins to 48 mins, depending on the extraction distance. Tiernan's study was conducted in Ireland, and shows results that are similar to the ones predicted in this study.

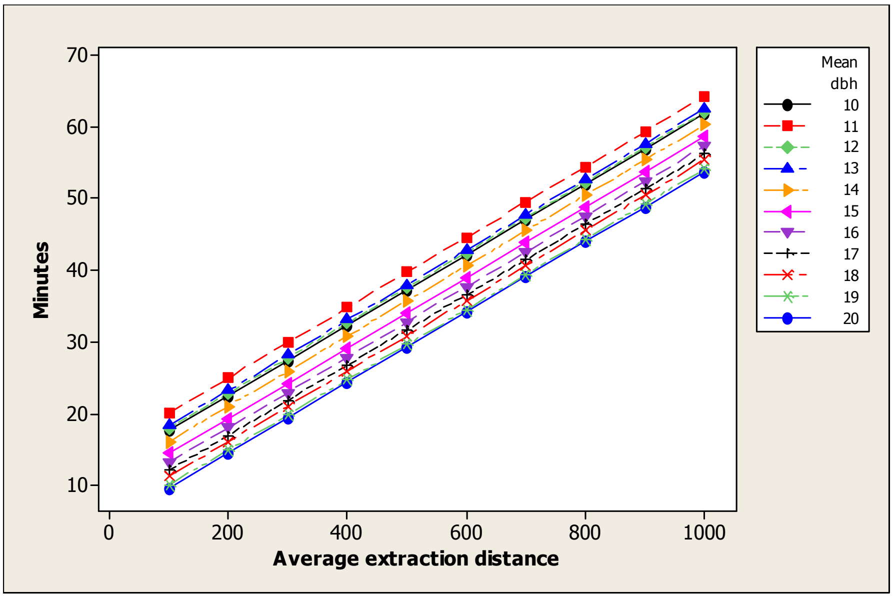


Figure 4.10: Predicted productivity of the CTL forwarder in Sitka spruce plantations at first thinning

Interestingly, it can be seen from the graph that the results for the small dbh levels are not as expected. According to the forwarder model, smaller piece sizes should cause a longer extraction cycle. However, the results show that a stand with a mean dbh of 10 cm will have a shorter forwarder extraction cycle than stands with mean dbh levels of 11 cm, 12 cm, or 13 cm. Conventional thought suggests that the mean log size should reflect the mean dbh level accordingly, that is; the smaller the mean dbh, the smaller the mean log size. An investigation into this shows that at a mean dbh level of 10 cm, very few trees have CTL product volume, and the trees that do are on the upper side (right side) of the distribution. The dbh distribution is a Weibull function (as described in chapter 3), and therefore, in the mean dbh levels just above 10cm, i.e. 11 cm, 12 cm, and 13 cm, a higher proportion of the log volumes will be to the left side of the distribution. Figure 4.11 illustrates this occurrence.

It must be noted that the absolute volumes predicted per hectare are very different for each dbh level (table 3.7). At a mean dbh level of 10 cm, only 3 cubic metres per hectare is estimated. At a mean dbh level of 13 cm, this estimation is for 19 cubic metres. It’s reasonable to suggest that there is an effect on productivity from the low density of log bunches distributed across the site. The time the forwarder would have to spend travelling between small bunches of logs would increase the cycle time. However this could not be investigated in this simulation study.

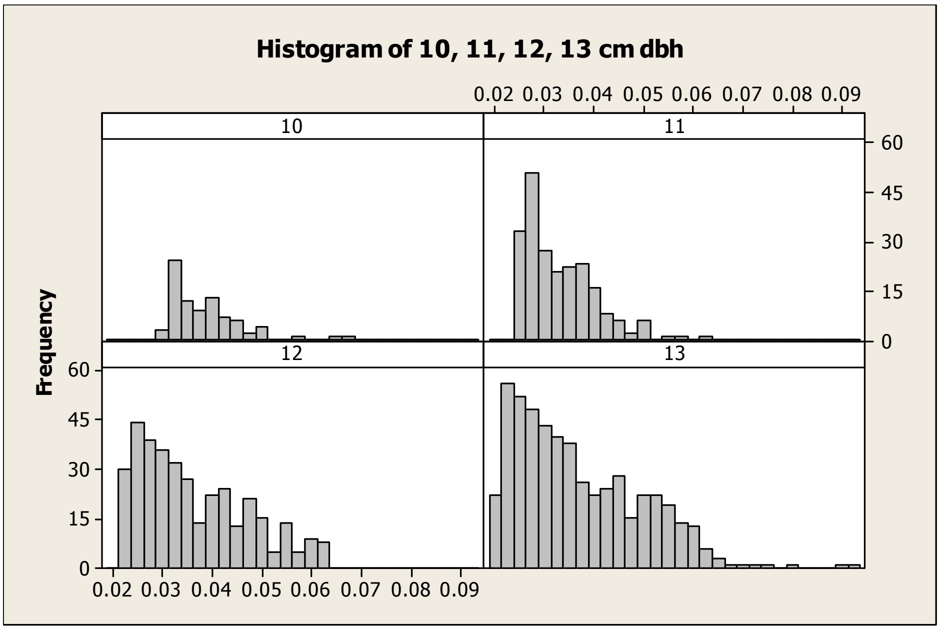


Figure 4.11: Predicted distributions of CTL volumes for 10-13 cm mean dbh levels for Sitka spruce plantations at first thinning. X-axis is in m^3

The cost per cubic metre of the forwarder operation is detailed in figure 4.12 below. The results are equivalent to the cycle time results, with the cost of 100.3 per m^3 included. The results show a cost range from €23 to €7 at a mean dbh level of 10cm, depending on extraction distance. And a range from €20 to €4 at a mean dbh level of 20cm.

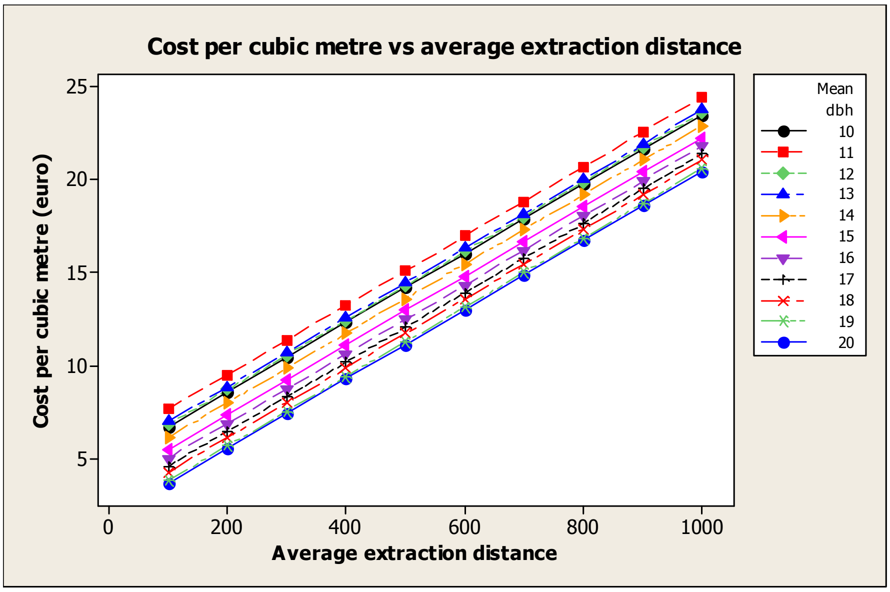


Figure 4.12: Predicted cost of production of the forwarder in Sitka spruce plantations at first thinning

4.4 Concluding remarks

A model has been developed to predict the productivity and cost of a harvester working on a first thinning Sitka spruce site in Ireland. The models independent variable is harvested volume, which can be estimated for a forest from the data in chapters 2 and 3. The harvester productivity has shown to increase as tree size increases, and conversely, the cost decreases as tree size increases. The machine rate per productive machine hour has been estimated as €129, which gave costs of between €285 and €12 euro per cubic metre, depending on the mean dbh level of the stand. The way in which the data has been collected for the harvester model is not a very robust approach. The volumes of the assortments are an indirect estimate. The mean volume for the assortment on the site is used. It is quite possible that the slope of the linear model would be different if actual volumes were known. To measure every individual log is not practical in the field. In the conclusions chapter of this dissertation, another method is proposed which could possibly give a better estimation and could improve future model development. It must be noted that the model can only be used for interpolation, and not extrapolation, as the quadratic equation used will predict unreasonable results for independent variable values outside the range that were used to develop the model.

A model was also developed for forwarder productivity using average extraction distance, load volume, and number of pieces as the independent variables. It was found that forwarder productivity reduced with increasing extraction distance. It was also found that forwarder productivity reduced with decreasing piece size. The machine rate per productive machine hour was estimated at €100, which projects costs in the region of between €4 and €24 per cubic metre, depending on extraction distance, when extracting and mean dbh level of the stand. In general, forest managers will want to delay thinning until the trees are of sufficient size that costs are minimized. The models developed in this chapter may help inform forest practitioners of the suitability of their stands for harvest, in terms of being able to recoup costs. However, there is a caveat that must be explicitly stated when using these operational cost based models as a decision support tool: thinning operations are a silvicultural practice, and so any decision to thin must be primarily decided within the limits of good silvicultural practice, or else future revenue streams will be greatly affected.

Chapter 5: Productivity and cost of roadside chipping of cut to length logs

5.1 Introduction

Across Northern Europe, chipping on the forest road is considered the most traditional location for the comminution of forest material. At the roadside, chips are commonly blown directly into large trailer trucks, making the operation vulnerable to delays caused by the transport trucks, and vice versa (Hakkila, 2004). In Italy it is commonplace for chip producers to have a loader on site with which the truck drivers can use to load their own trucks, making the system less susceptible to delays as the chippers can produce the woodchip in heaps on the ground (Spinelli and Hartsough, 2001). The primary reason for chipping at the forest roadside is that the parent material for most chips is forest residues; the branches and tops of the harvested trees that are not converted into roundwood products. These residues are extracted to the roadside, stacked and chipped. The chipping increases the bulk density of the biomass for transportation (Hakkila, 2004). On the other hand, chipping of roundwood logs decreases the bulk density (Kent et al., 2011). In Ireland, the extraction of forest residues to the roadside for chipping has not been greatly adopted as of yet, nor has the supply chain been investigated to a major extent. The majority of wood fuel suppliers operate a system where cut to length logs are used as the raw material for woodchip.

The aim of this chapter is to evaluate the productivity and cost of two chippers, a Musmax T8 and a Jenz 700, chipping cut to length logs at the forest roadside.

5.2 Materials and Methods

A Musmax T8 powered by the PTO of a Valmet 165 KW tractor, and a self powered 450KW Jenz 700 chipper were trialed in this study. Both machines were Irish owned and operated. In each chipping operation, the woodchip was blown directly into either truck trailers, or tractor trailers, for transport directly to the consumer. The trailers ranged in size from 30 m^3 to $80m^3$. The Musmax T8 was studied on four sites, Abbeyfeale in Co. Limerick, Ballybofey in Co. Donegal, Bweeng in Co. Cork, and Woodberry in Co. Galway. The Jenz 700 was observed on one site only; Woodberry in Co Galway. It had been planned that the Jenz 700 would operate on at least two other sites, however, on one site (Toormakeady in Co. Mayo), the gradient of the forest road was too steep, and the chipper could not be towed into place, despite many attempts. On the other site (Abbeyfeale in Co. Limerick), the contractor was unavailable to work. Table 5.1 details the site descriptions.

Table 5.1: Description of the sites used in the chipper study

Site	Site Area	Age	Stocking	Mean Dbh	Top Height	Yield Class
	ha	years	stems ha^{-1}	cm	m	m^3 ha^{-1} yr^{-1}
Abbyfeale, Co. Limerick	9.8	20	2191	17	13.5	22
Ballybofey, Co. Donegal	21	13	2455	14	11.2	24
Bweeng, Co. Cork	10	17	2251	13	11.1	23
Woodberry, Co. Galway	26.6	17	2199	15	12.3	24

The chipping operations have only a few time elements, and so, a stopwatch and field sheet was used to carry out a cycle based time study. Both the productive and unproductive time of the chipping operations were recorded. A cycle of a chipper was defined as the process of filling the container into which the chipper was chipping, i.e. either the truck or tractor trailer. Along with the time elements, a count of the number of logs was also recorded. Each cycle was divided into the following elements:

- Waiting to chip
- Chipping
- Delay

The waiting to chip element involved the time spent waiting for tractors or trucks to return to the chipper for loading. The haulage system used to transport the material off site was not a part of this study, and so any time spent waiting on the transport vehicles was not considered as effective time. The chipping element included the chipping of the logs, and the movement of the chipper along the stack as it chipped. The delay element included any other time spent on breakdowns or maintenance. In other literature, a maneuvering time element is sometimes included to account for the relocation of the chipper (Asikainen and Pulkkinen, 1998). However, in this study the stacks on each trial site, and their location, required that the chippers only ever moved a few meters at a time.

Relating the chipper cycle times to a unit of production was difficult. In order for the productivity of the chippers to be compatible with the taper and dbh/height models developed in chapter 2, the unit produced needed to be in cubic metres of solid volume. A bulk volume to solid volume conversion factor was developed for each individual cycle, and this was used to estimate the solid volume in each trailer. The conversion factors were calculated using sample data taken from each trailer during the chipping; for every $7.5m^3$ bulk volume chipped, a 60 litre sample was taken. The bulk density as received of each sample was estimated using a 50 litre stainless steel pot. Three moisture content sub samples were taken from each bulk density sample. Moisture content was calculated on a wet basis, using the oven dry method at 105 degrees Celsius. The bulk density as received was converted to bulk density dry matter using the moisture content results. The ratio between bulk density dry matter and the basic density of the wood was used to calculate the conversion factor. The basic density of Sitka spruce was not measured in this study, but a value for first thinning Sitka spruce of 447 kg/m^3, as published in Kent *et al.* (2011), was incorporated into the calculations. The complete process of estimating the solid volume for a cycle can be described in the equation below:

$$V_{solid_i} = V_{bulk_i} \times \frac{(1 - MC\%_i/100) \times BD_{ar_i})}{447}$$

Where:

V_{solid_i}= the solid volume (m^3) for the *ith* cycle

V_{bulk_i}= the bulk volume produced in the *ith* cycle (bulk volume of transport trailer) (m^3)

$MC\%_i$= moisture content percentage on a wet basis for the *ith* cycle

BD_{ar_i}= bulk density (kg/m^3) as received for the *ith* cycle

Other publications have related the productivity of chipping to piece size, that being the size of the logs (or other form) being fed into the chipper (Spinelli and Hartsough, 2001) .In order to estimate the mean piece size per cycle in this study, the estimated solid volume in a cycle was divided by the log count taken during the time study. Regression analysis in the R 2.14.1 statistical package was used to investigate the relationship between piece size and production time.

The machine rate calculations were estimated using the method by Miyata *et al.* (1980), as per the harvesting studies in chapter 4. The assumptions used in the machine rate calculations are presented in table 5.2.

Table 5.2: Machine rate calculation assumptions for roadside chippers

Rate	Unit	Musmax T8 Amount	Jenz 700 Amount
Initial Investment	Euro	205000[a]	475000[d]
Machine Power	kw	165[a]	450[d]
Salvage Value	% of investment	20[b]	20[b]
Salvage Value	Euro	41000	95000
Economic Life	years	5[b]	5[b]
Scheduled Operating hours	hrs/year	2000[b]	2000[b]
Utilisation Percentage	%	70[c]	65[b]
Productive Machine Hours	hrs/year	1400	1300
Interest Rate	%	8.5[b]	8.5[b]
Insurance and tax rate	%	4.0[b]	4.0[b]
Repair and Maintenance	% of depreciation	120[b]	120[b]
Depreciation	Euro/year	32800	76000
Average Yearly Investment	Euro/year	139400	323000
Interest	Euro/year	11849	27455
Insurance and Tax	Euro/year	5576	12920
Maintenance and Repair	Euro/pmh	28	70
Fuel Consumption Rate		0.11[b]	0.11[b]
Cost of litre of fuel		0.92[b]	0.92[b]
Fuel	Euro/pmh	17	46
Lubrication Consumption Rate		0.35[b]	0.35[b]
Lubrication	Euro/pmh	6	16
Labour	Euro/smh	15.5[b]	15.5[b]
Benefits	Euro/smh	5.43[b]	5.43[b]
Overheads %	%	5.0[b]	5.0[b]
Operating Profit %	%	9.0[b]	9.0[b]
Ownership cost per SMH	Euro/smh	25	58
Ownership cost per PMH	Euro/pmh	36	89
Operating cost per PMH	Euro/pmh	81	163
Operating cost per SMH	Euro/smh	56	106
Overheads per SMH	Euro/smh	4	8.2
Operating Profit Per SMH	Euro/smh	8	15.6
Total Rate per SMH	Euro/smh	93	189
Total Rate per PMH	Euro/pmh	133	290

Sources: [a] Pat Maloney, machine owner, [b] (Murphy et al., 2010), [c] (Kent et al., 2011) [d] Mark Hanley, machine owner

5.3 Results and discussion

5.3.1 Musmax T8 Time Consumption analysis

Table 5.3 details the individual cycle results for the Musmax time study. As many cycles as possible were captured on each site, however, the absolute volumes that were chipped on some sites were small; the Abbeyfeale site only had enough material for two cycles, the Bweeng site only had enough for one. Unfortunately, on these two sites, large containers of 80 m^3 were used to chip into. If smaller containers had been used, the operations could have been segregated into more cycles. A total of 26.5 hours were recorded during the study, capturing 12 cycles. Between 80 m^3 and 50 m^3 bulk volume was chipped in each cycle, depending on the size of the transport container, and in total, 735 m^3 of wood chip was produced in the study. The samples taken from each load estimated the mean moisture content range from 42% to 57%, and this estimated the bulk density dry matter range of 127 kg/m^3 to 161 $kg/m^{3.}$ The bulk volume to solid volume conversion factors for the Musmax T8 were estimated to be between 0.29 and 0.34. This gave a solid volume per cycle of between 16.36 m^3 to 24.05 m^3 (also depending on the size of the trailer into which the chipper was chipping). The waiting to chip time element was not counted as effective time, as the transport system in place was not part of this study, and alternatives could have been used (such as chipping into heaps). The delay element was also not counted as effective time. Overall, the delay free productive time of a cubic metre of solid volume was between 3 mins and 7mins. This equates to a productivity range of between 9 and 20 cubic metres solid volume per hour.

Table 5.3: Individual cycle results for Musmax T8 time study

Cycle No.	Site	Waiting to chip (centimins)	Chipping (centimins)	Delay chipping (centimins)	Bulk vol. (m^3)	Bulk density (kg/m^3)	Moisture Content %	Bulk density of dry matter (kg/m^3)	Bulk vol. to solid vol. conversion factor	Solid volume (m^3)	Mean Piece vol. (m^3)	Cycle time per m3 solid
1	Abbeyfeale	1200	7032	648	80	248	48	130	0.29	23.24	0.042	303
2	Abbeyfeale	7132	11615	1240	80	289	54	134	0.30	24.05	0.029	483
3	Ballybofey	512	5948	632	60	281	52	135	0.30	18.14	0.036	328
4	Ballybofey	5425	6238	0	60	298	57	127	0.29	17.10	0.032	365
5	Ballybofey	13928	6368	0	60	314	56	138	0.31	18.57	0.034	343
6	Ballybofey	4243	6043	0	60	324	59	132	0.29	17.69	0.033	342
7	Ballybofey	1020	8020	0	55	311	55	138	0.31	17.02	0.030	471
8	Bweeng	3062	10477	768	80	285	47	152	0.34	27.21	0.030	385
9	Woodberry	2640	9835	585	50	329	55	147	0.33	16.50	0.014	596
10	Woodberry	6550	9143	278	50	312	53	146	0.33	16.36	0.025	559
11	Woodberry	5503	7625	0	50	259	42	150	0.34	16.83	0.024	453
12	Woodberry	2580	12248	630	50	344	53	161	0.36	18.00	0.020	680

Figure 5.1 below illustrates the aggregated time consumption for the Musmax T8 during the study. The majority of the time the machine was productively chipping, accounting for 63.2% of the time. Delays only accounted for 3%, while waiting to chip accounted for 33.8%. The high waiting to chip time was caused by the lack of an efficient haulage system for the wood chip. The chipper had to spend a large amount of time waiting for a haulage vehicle to return from delivering the chip. A better system with more haulage vehicles was not set in place as the study was not a long term trial, and as the contractor was not accustomed to the logistics of chipping in the forest, only a few haulage vehicles were employed.

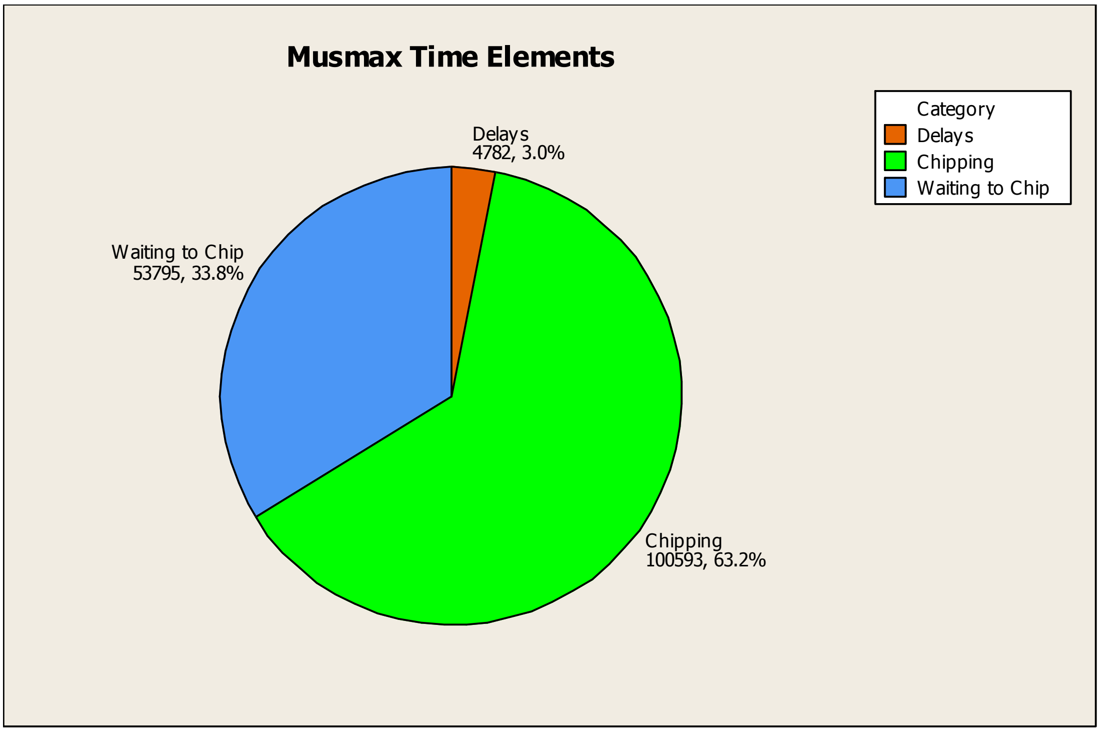


Figure 5.1: Time consumption for Musmax T8 chipping at the forest roadside during the time study

5.3.2 Jenz 700 time consumption analysis

Table 5.4 below details the time consumption analysis of the Jenz 700 during the trial. A total of 13 cycles were captured, all on the Woodberry site. It had been intended that the chipper would also work on two other sites, however, site conditions and the contractor's availability prevented this (as explained earlier in the text). The study recorded 4.9 hours of the machine's operation, which captured 13 cycles. There was no delay recorded in the study as the machine was constantly available for work. Two tractor trailers were used to haul the chip to a nearby consumer; the trailers were 33 m^3 and 30 m^3 bulk volume. The bulk density of the chip ranged from 240 kg/m^3 to 320 kg/m^3. The moisture content of the chip ranged from 30% to 47%. The bulk density and moisture content were used to estimate the bulk density dry matter for each load, which was estimated as having a range of 157 kg/m^3 to 198 kg/m^3. The bulk volume/solid volume conversion factor was estimated to be between 0.34 and 0.44, and these estimates calculated the solid volume per cycle as being between 10.3 m^3 and 13.32 m^3. As per the Musmax dataset, the waiting to chip element was not counted as effective time. The delay free production time per cubic metre solid volume was estimated to range between 71 and 110 centimins.

Table 5.4: Individual cycle results for Jenz 700 time study

Cycle No.	Site	Waiting to chip (centimins)	Chipping (centimins)	Delay chipping (centimins)	Bulk vol. (m^3)	Bulk density (kg/m^3)	Moisture Content %	Bulk density of dry matter (kg/m^3)	Bulk vol. to solid vol. conversion factor	Solid volume (m^3)	Mean Piece vol. (m^3)	Cycle time per m3 solid
1	Woodberry	3085	950	0	30	300	34	198	0.44	13.30	0.066	71
2	Woodberry	605	990	0	33	320	44	180	0.40	13.32	0.056	74
3	Woodberry	0	1017	0	30	293	41	174	0.39	11.66	0.051	87
4	Woodberry	2132	927	0	30	302	38	186	0.42	12.49	0.056	74
5	Woodberry	188	865	0	30	279	45	154	0.34	10.30	0.027	84
6	Woodberry	337	902	0	30	295	45	161	0.36	10.83	0.028	83
7	Woodberry	2855	1095	0	33	298	47	158	0.35	11.65	0.038	94
8	Woodberry	735	1295	0	33	244	34	160	0.36	11.80	0.027	110
9	Woodberry	3147	1042	0	30	273	40	163	0.36	10.93	0.028	95
10	Woodberry	217	1150	0	33	225	30	157	0.35	11.58	0.031	99
11	Woodberry	2423	1002	0	30	238	32	163	0.37	10.96	0.037	91
12	Woodberry	447	1205	0	33	240	34	160	0.36	11.78	0.034	102
13	Woodberry	0	1058	0	30	265	37	168	0.38	11.25	0.037	94

Figure 5.2 displays the time consumption analysis for the Jenz 700 chipper over the study period. It was found that the waiting to chip element accounted for 55% of the time, which was actually higher than the productive chipping element, which only accounted for 46% of the time. Again, this illustrates the affect an inefficient haulage system can have on the systems productivity.

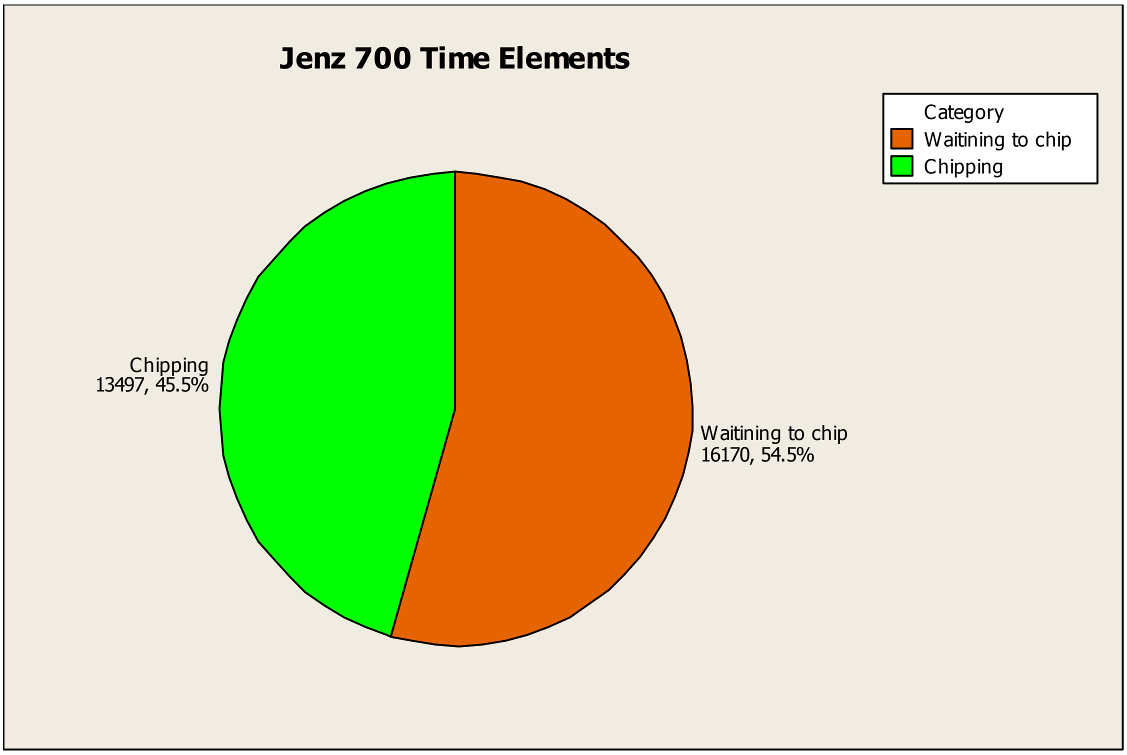


Figure 5.2: Time consumption for Jenz 700 chipping at the forest roadside during the time study

5.3.3 Further Analysis: Development of productivity models

It was considered useful to parameterize the productivity of the chippers with the variable of piece size. The productivity of the chippers could then be used with the data from chapter 2 and 3. The first concern that needed to be addressed was the evaluation of any site effect in the

Musmax T8 data. As the data came from different sites, any site effects would need to be identified before a relationship could be described. An analysis of covariance (ANCOVA) was performed in a general linear model (GLM) in the Minitab 16 statistical software package. The analysis was to identify any difference caused by the site when the effect of piece size was taken into account. The ANCOVA results are detailed in table 5.5. The data shows that the piece volume has a significant effect (p value 0.027), while site does not when piece size is adjusted for (p value 0.554). Analysis was carried out with an alpha level of 0.05.

Table 5.5: General linear model analysis of covariates for the Musmax T8 sites

Source	DF	Seq SS	Adj SS	F	P
Piece Vol.	1	123129	29762	7.79	0.027
Site	3	8646	8646	0.75	0.554
Error	7	26757	26757		
Total	11	158531			

Next, the R 2.14.1 statistical package was used to investigate the relationship between piece size and production time. For both chippers, straight line linear equations fit the data best, and so the models took the form of:

$$Production\ time\ per\ m^3 = \beta_0 + \beta_1 Mean\ Piece\ Vol.$$

The results from the regression analysis are detailed in table 5.6. Both regression models are shown to be statistically significant at an alpha level of 0.05. The Musmax equation has a high R^2 value of 0.78, indicating a large amount of the variation in the data is explained by the model. The Jenz equation has an R^2 value of 0.56, indicating that less of the variation in the data is explained by the model. No other variables were measured that could be used as independent predictors of productivity, and so the R^2 of the Jenz model could not be improved.

Table 5.6: Parameter estimates for the roadside chipping models

	Musmax		Jenz	
Coefficient	Estimate	SE	Estimate	SE
β_0	858	73	116	7
β_1	-14221	2411	-664	179
P value	0.00012		0.00346	
R^2	0.78		0.56	

A graph of each regression model is present in figure 5.3 and figure 5.4. An analysis of the residuals shows that the Musmax data is normally distributed around the model with a P value of 0.14 from an Anderson Darling test. The Jenz 700 residuals also have shown to be normally distributed around the model with a P value of 0.92 from an Anderson Darling test. The cycle times of the chippers are predicted as being between 6.5 mins per m^3 and 2.7 min per m^3 for the Musmax T8, and between 1.0 mins per m^3 and 0.7 mins (42 secs) for the Jenz 700, depending on the piece size. Spinelli and Hartsough (2001) found productivity trends for chipping machines similar to the ones found here. In their study, they found the majority of conditions allowed the chippers to operate at a rate of 1 tonne in less than 10 mins, while the larger chippers were able to operate at a rate of approximately 1 tonne per min.

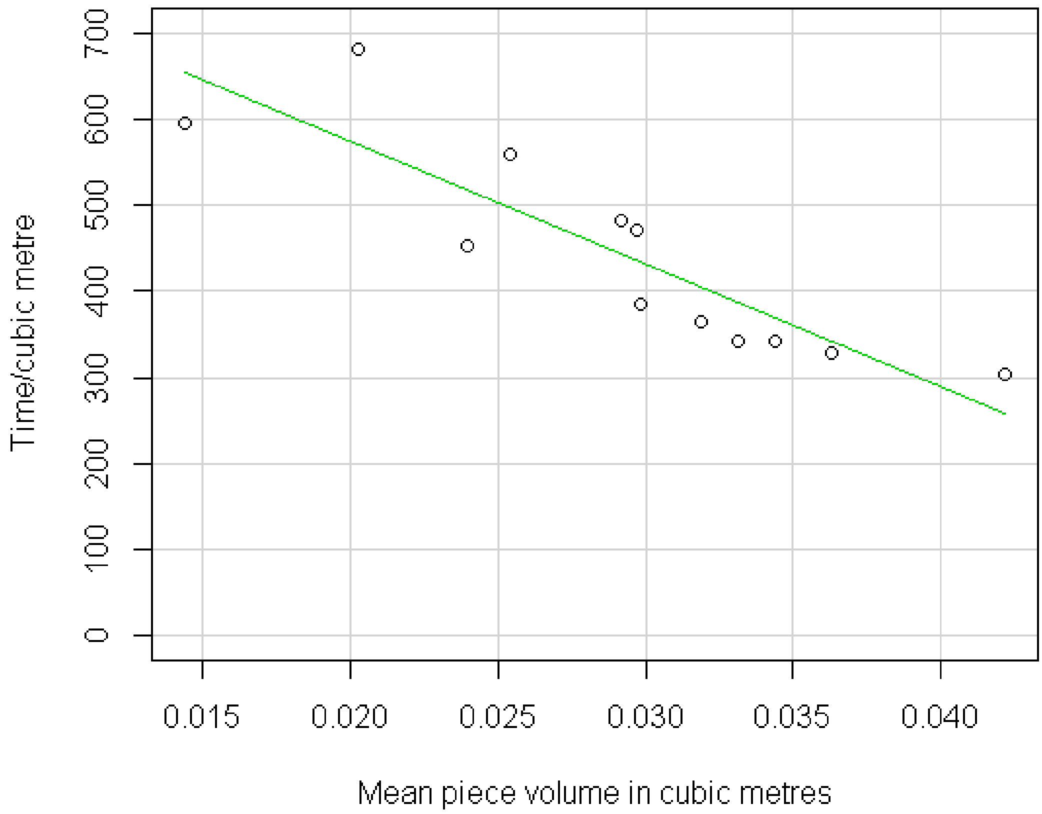


Figure 5.3: Scatterplot of Musmax T8 data observed during the study with a regression line describing the relationship between mean piece volume and production time per m^3

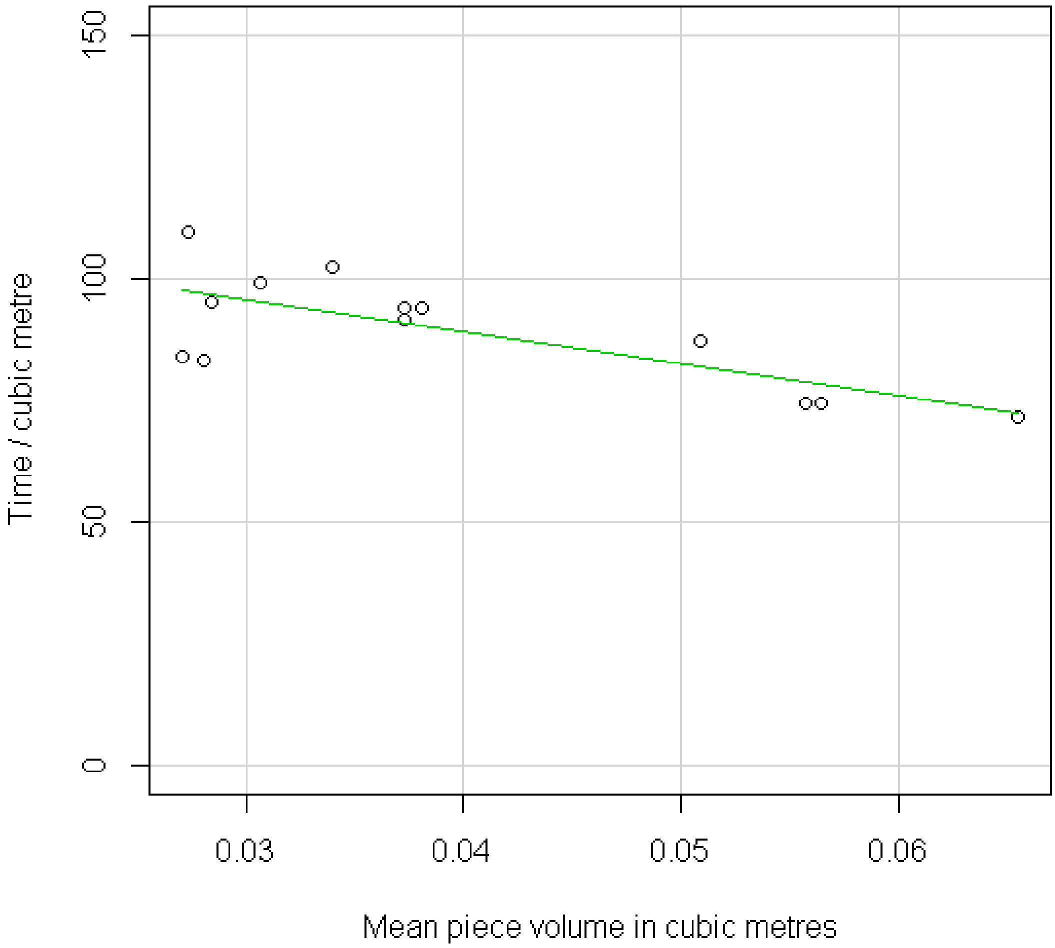


Figure 5.4: Scatterplot of Jenz 700 data observed during the study with a regression line describing the relationship between mean piece volume and production time per m^3

Two models for roadside chipping productivity as experienced during the trial can now be given as:

$$Musmax_t = 858 - (14221 \times Piece_{vol})$$

$$Jenz_t = 116 - (664 \times Piece_{vol})$$

Where:

$Musmax_t$ = Musmax T8 productive time (centimins) per cubic metre solid volume

$Jenz_t$ = Jenz 700 productive time (centimins) per cubic metre solid volume

$Piece_{vol}$ = Mean log volume (m^3)

The cost of production can be estimated from these models by adding terms for the scheduled machine cost per hour, so that:

$$Musmax_{cost} = \frac{133}{60/[(858 - (14221 \times Piece_{vol}))/100]}$$

$$Jenz_{cost} = \frac{290}{60/[(116 - (664 \times Piece_{vol}))/100]}$$

Where:

$Musmax_{cost}$= Musmax T8 cost per cubic metre of solid volume (€)

$Jenz_{cost}$ = Jenz 700 cost per cubic metre of solid volume (€)

$Piece_{vol}$ = Mean log volume (m^3)

The dbh distributions developed in chapter 3 were used to generate data to input into the chipper models, to simulate the productivity of the chippers at different levels of mean dbh. For each dbh generated, the dbh/height model and taper model were applied to calculate the assortment volumes present. The CTL product dimension specifications used are described in chapter 3 (table 3.4). In this study, the pulp assortment was used for chipping as it is the lowest value product. The pallet and sawlog products, if present, should be sold to the mills. This will be discussed further in chapter 8. The input to the chipper models (mean piece size) is calculated at each mean dbh level as the average pulp log volume predicted by the taper model. Figure 5.5 below illustrates the results. The Musmax model can only predict up to a mean piece volume of $0.042m^3$, and therefore is only reliable for a portion of the data. The Jenz 700 can predict for all mean dbh levels. The results shows that the cost of production using the Musmax chipper ranges from €6.9 / m^3 to €8.7 / m^3. The results also show that the Musmax chipper is a lot more sensitive to a change in piece volume than the Jenz 700 chipper. The Jenz 700 is predicted as having a cost of production of €4.6 / m^3 to €3.7 / m^3.

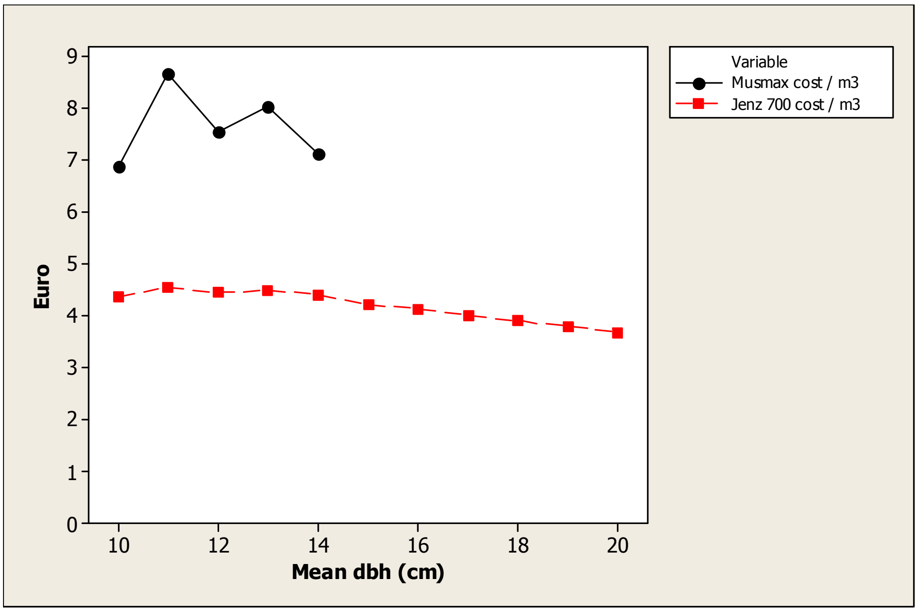


Figure 5.5: Predicted cost of production of the roadside chippers chipping at the forest road in Sitka spruce plantations at first thinning

5.4 Concluding remarks

It has been possible to model the productivity of the Musmax T8 and Jenz 700 chipping roundwood logs produced from a CTL harvesting system. The chippers operated on the forest road. The productivity estimates are calculated on a solid wood volume basis (m^3), as this is the unit that forest inventory estimates. Thus, the taper and dbh/height models developed in chapter 2, along with the simulated datasets in chapter 3, can be used directly with the productivity equations developed in this chapter. It was found that piece size was the most important factor affecting chipper productivity. The two chippers, the Musmax T8 and Jenz 700 are estimated to convert one cubic metre of solid volume to woodchip at a cost of in the region of €5.29 to €9.68, and €3.31 to €3.69 respectively. As the chippers were located at the forest roadside, they were unaffected by the majority of site conditions. However, if roadside chipping is to be used extensively in Ireland, further investigations on the forest road network and its suitability for maneuvering both chippers and haulage vehicles into position for chipping. Also, discrete event simulation could be employed to model the interaction between the chippers and haulage vehicles.

Chapter 6: Productivity and cost of whole tree harvesting and terrain chipping in a Sitka spruce first thinnings

6.1 Introduction

Harvesting of small diameter trees may only be feasible when the method includes an integration of merchantable log volumes and residues for energy, as the absolute log volumes will be small (Asplund et al., 1999). Whole tree harvesting provisions for this, as the non-merchantable stem and branches are recovered. Typically, especially in the U.S. and Canada, the trees are felled and pulled out of the forest and processed at the landing. This usually requires four machines; a feller-buncher, skidder, loader, and processor. The feller-buncher fells and aggregates trees for the skidder, which drags these bunches to the landing. The trees are converted into logs at the landing by a processor and then are put onto a truck using a loader. Even though whole tree harvesting systems require more machines than cut to length systems, cut to length systems require more financial investment due to their complex parts and computerisation. However, whole tree systems are more management intensive, as the machines interact directly with each other (Adebayo et al., 2007). Skidding of stems out of the forest can cause soil compaction and damage as dragging trees can remove litter, exposing the mineral soil beneath. Also damage to the remaining crop often occurs, especially to younger stems from the dragged material (Hartsough et al., 1997).

The British Forestry Authority’s Whole-Tree Harvesting Guide (Nisbet et al., 1997) describes how whole tree harvesting had not been traditionally practiced in the UK, however in the 1990’s two systems were introduced, a one stage system where the whole tree is removed by skidder or cable system, and a two stage where a cut to length system is employed and the residues are removed by the forwarder in a second pass. These systems were brought in for a number of reasons in the UK; it was perceived that the removal of brash would make restocking quicker, easier and cheaper, the woody material would be marketed as fuel/mulch, and it improved the visual appearance of harvested sites (Nisbet et al., 1997).

In the case of pre-commercial thinnings where merchantable material is not attainable in sufficient volume to cover the cost of their production, terrain chipping systems can be used for whole tree utilisation. Terrain chipping is a system whereby a chipper is mounted to a mobile machine which drives off-road into the forest, chipping the material as it moves. The system is also often used for residues after clearfell. Purpose built terrain chippers are typically built onto forwarder chassis, and have a 10 to 20 m^3 container into which the chips are blown. When full, the chip in the containers is tipped into a specialised chips forwarder which transports the chips to the landing. Terrain chippers can also be retro fitted to existing machinery, where the chipping mechanism is mounted, for example, on the three-point linkage of an agricultural tractor. On smaller sites, a terrain chipper may work alone, hauling the material to the landing when full (Savolainen and Berggren, 2000). Only using one machine in this way for both chipping and forest haulage, the cost of machine relocation and set up/tear down is reduced. On smaller sites this may make the thinning operation financially viable. (Hakkila, 2004) Terrain chippers tend to be too heavy for soft ground. Although there are requirements for terrain chipping equipment to be as light as possible, there is a trade off between lightness and strength and stability (Kofman and Kent, 2009, Hakkila, 2004, Richardson, 2002).

Whole tree thinning using terrain chipping is extensively used in Denmark in a 2 stage system. In the first stage, motor manual operators (chainsaw) perform in a systematic line thinning. The trees are directionally felled in the line with all the butts facing the same direction. The trees are left in the line to dry for a period of time, and then a terrain chipper drives up the lines chipping as it goes. The chip is transferred to a chips forwarder which extracts the chip to the roadside. In the second stage, a selection thinning is carried out between the lines using a feller buncher, and the trees left in the line as before. The terrain chipping system is then used to chip the trees as per stage 1. There is usually a year between the two stages (Kofman and Kent, 2009).

The objective of this chapter is to estimate the productivity of whole tree harvesting of Sitka spruce during a first thinning, and to make a first evaluation of the parameters affecting terrain chipping of the whole trees. The modeling of a terrain chipper and chips forwarder productivity is done in a way that allows the discrete event simulation of the chipping system in chapter 7.

6.2 Materials and methods

6.2.1 Motor manual line thinning of whole trees

Chainsaw felling of Sitka spruce whole trees during a line thinning was studied on 5 first thinning plantation sites in Ireland. Table 6.1 details the site descriptions. The thinning removed every 7th line. Different chainsaw operators worked on each site. The trees were felled in a single direction onto the extraction rack so that all tree butts were facing the same way. It was ensured that the tree butts were totally removed from their stumps to prevent further uptake of moisture from the root system. No cross cutting or delimbing took place, and the whole tree was left intact on the forest floor.

Table 6.1: Site descriptions of the sites used in the chainsaw felling study

Site	Species	Plot Area	Age	Stocking	Mean dbh	Top height
		ha	year	stems/ha	cm	m
Abbeyfeale	Sitka spruce	3.2	20	2277	17	13.5
Ballybofey	Sitka spruce/Larch	3.3	13	2210	14	11.2
Bweeng	Sitka spruce	3.0	17	2566	12	10.8
Toormakeady	Sitka spruce	3.5	16	2915	12	10
Woodberry	Sitka spruce	4.8	17	1919	18	13.5

A continuous cycle based time study was carried out to evaluate the time consumption of the chainsaw harvesting. A husky hunter field computer running the Siwork3 time study software was used to record the time elements of each cycle. A cycle was defined as the operation of felling one tree. Each cycle was divided up into the following elements;

- Select
- Fell
- Down
- Urea

- Delays

As the thinning operation was purely systematic, the selection of the trees was pre-determined, however, a selection time element was used to record the time taken to visually inspect the tree and make decisions on the felling technique required. The fell element included the time required to prepare the base of the tree, and to make the felling cuts. The down cycle element recorded the time take after the felling cuts were made to the moment when the tree is presented lying in the line with the butt totally removed from the stump. The urea time element comprised of the time taken to apply urea on the stump after the tree was felled. Each operator had a small hand sprayer which was used to apply the urea.

Unfortunately, no dimensional measurements were taken during the time study, and so productivity of manual felling cannot be related to a function of tree size. An approach that was used in the IRLPACA model by Murphy *et al.* (2010) was adopted; in cases where insufficient data was available to relate productivity in cubic metres to some tree dimension, Murphy used the productivity unit of trees/hour. This allowed Murphy to predict the costs of the operation based on the number of stems to be harvested. It also means that the cycle time does not change as tree size increases or decreases, which is a major limitation to this study. It assumes that the time to harvest a tree will be the same regardless of its size, and so productivity per m^3 will increase directly proportionally as tree size increases.

The machine rate calculations were based on the method described by Miyata *et al.* (1980). The assumptions for the machine rate cost of manual felling are detailed in table 6.2 below.

Table 6.2: Machine rate assumptions for motor manual felling

Rate	Unit	Amount
Initial Investment	Euro	650[a]
Machine Power	kw	NA
Salvage Value	% of initial investment	20[b]
Salvage Value	Euro	130
Economic Life	years	0.8[b]
Scheduled Operating hours	hrs/year	1500[b]
Utilisation Percentage	%	60[b]
Productive Machine Hours	hrs/year	900
Interest Rate	%	8.5[b]
Insurance and tax rate	%	4[b]
Repair and Maintenance	% of depreciation	700[b]
Depreciation	Euro/year	600
Average Yearly Investment	Euro/year	715
Interest	Euro/year	60.8
Insurance and Tax	Euro/year	28.6
Maintenance and Repair	Euro/pmh	5.1
Fuel Consumption Rate		NA
Fuel	Euro/pmh	0.7[a]
Lubrication Consumption Rate		NA
Lubrication	Euro/pmh	0.2[a]
Labour	Euro/smh	16.5[b]
Benefits	Euro/smh	5.8[b]
Labour	Euro/pmh	27.5
Benefits	Euro/pmh	9.63
Overheads %	%	5[b]
Operating Profit %	%	9[b]
Ownership cost per SMH	Euro/smh	0.5
Ownership cost per PMH	Euro/pmh	0.8
Operating cost per PMH	Euro/pmh	43.1
Operating cost per SMH	Euro/smh	25.9
Overheads per SMH	Euro/smh	1.3
Operating Profit Per SMH	Euro/smh	2.5
Total Rate per SMH	Euro/smh	30.1
Total Rate per PMH	Euro/pmh	50.2

Sources: [a] Tom O'Dwyer, machine owner, [b] (Murphy *et al.*, 2010)

6.2.2 Feller Buncher harvesting of selection trees between the lines

Data from a study of a Silvatec 656TH feller-buncher was used in this chapter. The study was published by Kofman and Kent (2007), and is directly applicable to this chapter as the trial included the terrain chipping of the trees in the stand after the thinning. The raw data from this study was received from the authors, and analysed for this chapter. The feller buncher performed a selection only thinning between racks which had already been harvested and chipped in a previous line thinning. The study was carried out on two Sitka spruce first thinning plantations. The feller-buncher operated by reversing down each rack, the operator selected and felled trees from lines each side of the rack, and lay them down into the middle of the rack with the butt ends all facing the same direction.

A husky field computer running the Siwork 3 software was used to record a continuous cycle based time study of the operation. A cycle was defined as the accumulation of a number of stems, and laying them on the rack, signified by the break point of emptying the felling head. Each cycle was divided into the following elements;

- Move
- Select
- Fell 1
- Fell 2
- Down
- Delays

The move element comprised of the time spent travelling in the forest, without any other element being performed. The select element involved the operator identifying the next tree to fell, and the positioning of the boom to the tree. The fell 1, and fell 2 elements represent the time spent cutting the trees from their stumps. No more than two trees were ever felled in a cycle. The down element comprised of the placing of the accumulation in a horizontally in the middle of the rack.

Unfortunately, similar to the motor manual felling, no tree dimensions were recorded along with the time study which can be used to relate the productivity to tree size. Preliminary analysis of regression with the mean site values showed no useful significance. The same method as the motor manual felling was adopted, where productivity was estimated as trees/hour.

The machine rate cost calculations were estimated using the method described by Miyata *et al.* (1980). The assumptions of the machine rate cost for the feller buncher are detailed in table 6.3 below.

Table 6.3: Machine rate calculation for the feller buncher

Rate	Unit	Amount
Initial Investment	Euro	265000[a]
Machine Power	kw	110[a]
Salvage Value	Euro	53000[a]
Economic Life	years	6[a]
Scheduled Operating hours	hrs/year	2000[a]
Utilisation Percentage	%	75[a]
Productive Machine Hours	hrs/year	1500
Interest Rate	%	8.5[a]
Insurance and tax rate	%	4[a]
Repair and Maintenance	% of depreciation	100[a]
Depreciation	Euro/year	35333
Average Yearly Investment	Euro/year	176667
Interest	Euro/year	15017
Insurance and Tax	Euro/year	7067
Maintenance and Repair	Euro/pmh	23.6
Fuel Consumption Rate		0.062[a]
Cost of litre of fuel		0.92[a]
Fuel	Euro/pmh	6.3
Lubrication Consumption Rate		0.35[a]
Lubrication	Euro/pmh	2.2
Labour	Euro/smh	15.5[a]
Benefits	Euro/smh	5.425[a]
Labour	Euro/pmh	20.7
Benefits	Euro/pmh	7.2
Overheads %	%	5[a]
Operating Profit %	%	9[a]
Ownership cost per SMH	Euro/smh	29
Ownership cost per PMH	Euro/pmh	38
Operating cost per PMH	Euro/pmh	60
Operating cost per SMH	Euro/smh	45
Overheads per SMH	Euro/smh	4
Operating Profit Per SMH	Euro/smh	7.0
Total Rate per SMH	Euro/smh	84.3
Total Rate per PMH	Euro/pmh	112.4

Sources: [a](Murphy *et al*., 2010)

6.2.3 Terrain chipping of whole trees in a first thinning

A 205KW Silvatec terrain chipper was trialled on four first thinning sites in Ireland, the site descriptions are detailed in table 6.4 below. Previously on each site, a systematic thinning had been performed where 1 line in 7 was felled by chainsaw operators. The trees had been felled in a single direction, so that the terrain chipper could operate as efficiently as possible. During this trial, the terrain chipper drove down the felled line, feeding the whole trees butt end first with an equipped grapple arm into a front-mounted disc chipper. By chipping while driving, the chipper was in constantly production while it moved. The bunk of the terrain chipper had a volume capacity of $17m^3$. When full, the bunk was unloaded into a chips forwarder for extraction to the roadside. Ideally, the chips forwarder should return to the terrain chipper before its bunk was full again, that way the chipper would not have to wait to unload, and production could be constant.

Table 6.4: Site descriptions for the terrain chipper study

Site	Species	Plot Area	Age	Stocking	Mean dbh	Top height
		ha	year	stems/ha	cm	m
Abbeyfeale	Sitka spruce	3.2	20	2277	17	13.5
Ballybofey	Sitka spruce/Larch	3.3	13	2210	14	11.2
Toormakeady	Sitka spruce	3.5	16	2915	12	10
Woodberry	Sitka spruce	4.8	17	1919	18	13.5

A continuous cycle based time study of the terrain chipper was undertaken using a Husky Hunter field computer running the Siwork 3 software. A cycle was defined as the filling and unloading of one bunk of the chipper. Each cycle was divided into the following elements;

- Move
- Chipping
- Unloading
- Waiting
- Delays

The move element comprised of the movement of the machine, when no other time element was applicable. The chipping time element included the time when the terrain chipper was actively chipping as it moved down the lines. The waiting time element was associated with any time where the chipper had a full bunk, but could not unload it to the chips forwarder as the chips forwarder had not returned from the roadside yet. The unloading element involved the tipping of a full chipper bunk into the forwarder for transportation to the roadside. The delay element included any other time which was not applicable to the other elements. Along with the time elements, a count of the number of trees in each cycle was also recorded.

Like the roadside chippers, it was beneficial for the productivity of the terrain chipper to be expressed in cubic metres of solid volume. This would allow for the direct costing of machine operations from stand volume predictions. In the same manner as the roadside chippers, a bulk volume to solid volume conversion factor was developed for each cycle. The conversion factor was developed using samples taken from each load. Three 50 litre bulk density samples were taken per load, which were each further sub-sampled into three moisture content samples. The bulk density as received was converted to bulk density dry matter using the moisture content percentages, and the ratio between the bulk density dry matter and the basic density of Sitka spruce was used to calculate the conversion factor. Again, the basic density of Sitka spruce was not measured in this study, but a value for first thinning Sitka spruce of 447 kg/m^3, as published in Kent *et al.* (2011) was used. As per the roadside chippers, the complete process of estimating the solid volume for a cycle can be described in the equation below:

$$V_{solid_i} = 17 \times \frac{((1 - (MC\%_i/100) \times BD_{ar_i})}{447}$$

Where:

V_{solid_i}= the solid volume (m^3) for the ith cycle

V_{bulk_i}= the bulk volume produced in the ith cycle (bulk volume of transport trailer) (m^3)

$MC\%_i$= moisture content percentage on a wet basis for the ith cycle

BD_{ar_i}= bulk density (kg/m^3) as received for the ith cycle

Regression analysis using the Minitab 16 statistical package was used to investigate the relationship between productivity and mean piece size, where piece size is the solid volume of the whole tree. The mean piece size in a load was estimated from the solid volume and the count of the trees that was chipped in the load.

The machine rate calculations were estimated using the method by Miyata *et al.* (1980). The machine rate assumptions are detailed in the table 6.5.

Table 6.5: Machine Rate assumptions for the Silvatec terrain chipper

Rate	Unit	Amount
Initial Investment	Euro	650000[a]
Machine Power	kw	205[b]
Salvage Value	Euro	130000[c]
Economic Life	years	6[c]
Scheduled Operating hours	hrs/year	2000[c]
Utilisation Percentage	%	70[d]
Productive Machine Hours	hrs/year	1400
Interest Rate	%	8.5[c]
Insurance and tax rate	%	4[c]
Repair and Maintenance	% of depreciation	100[c]
Depreciation	Euro/year	86666
Average Yearly Investment	Euro/year	433333
Interest	Euro/year	36833
Insurance and Tax	Euro/year	17333
Maintenance and Repair	Euro/pmh	61.9
Fuel Consumption Rate		0.11[c]
Cost of litre of fuel		0.92[c]
Fuel	Euro/pmh	20.74c
Lubrication Consumption Rate		0.35[c]
Lubrication	Euro/pmh	7.3c
Labour	Euro/smh	15.5[c]
Benefits	Euro/smh	5.64[c]
Labour	Euro/pmh	22.14
Benefits	Euro/pmh	8.06
Overheads %	%	5[c]
Operating Profit %	%	9[c]
Ownership cost per SMH	Euro/smh	70.4
Ownership cost per PMH	Euro/pmh	100.6
Operating cost per PMH	Euro/pmh	120.1
Operating cost per SMH	Euro/smh	84.08
Overheads per SMH	Euro/smh	7.7
Operating Profit Per SMH	Euro/smh	14.6
Total Rate per SMH	Euro/smh	176.8
Total Rate per PMH	Euro/pmh	252.6

Sources; [a] Silvatec Agent Kevin Bannon, [b]Machine Operator, [c]Murphy *et al.* (2010), [d] Kent *et al.* (2011)

6.2.4 Chips Forwarder productivity and cost

A 125 kW Silvatec chips forwarder was trialled on four Sitka spruce first thinning sites in Ireland. The site descriptions are detailed in table 6.6. The chips forwarder was working in tandem with the same Silvatec terrain chipper studied in the previous section. Both operators were in constant communication with each other through 2-way radios so that the transferring of woodchip from chipper to forwarder was as efficient as possible. The chips forwarder unloaded the woodchip at the forest road into roll on-roll off containers. These containers were left on the forest road by haulage trucks. The trucks could then pick them up again once full. In Denmark, several containers would be distributed on the forest road in order to optimize the chips forwarder turnaround time. Similarly, road haulage productivity could be optimized as long as there were full containers in the forest. In this study, if no containers were available, the chips forwarder dumped the woodchip at the landing for reloading by excavator. By doing this, the forwarder was not influenced by the logistics of the haulage, and so prevented a knock on effect up the chain to the terrain chipper.

Table 6.6: Site descriptions for chip forwarder study

Site	Species	Plot Area	Age	Stocking	Mean dbh	Top height
		ha	year	stems/ha	cm	m
Abbeyfeale	Sitka spruce	3.2	20	2277	17	13.5
Ballybofey	Sitka spruce/Larch	3.3	13	2210	14	11.2
Toormakeady	Sitka spruce	3.5	16	2915	12	10
Woodberry	Sitka spruce	4.8	17	1919	18	13.5

A stopwatch and fieldsheet were used to conduct a cycle based time study of the chips forwarder. A cycle was defined as the operation of travelling from the roadside, loading woodchip from the chipper, transporting and unloading it at the roadside. Each cycle was divided into the following elements;

- Drive empty
- Loading
- Drive full
- Unloading
- Waiting
- Delays

The drive empty element comprised of the chips forwarder driving from the roadside unloading area to the terrain chipper in the forest. The loading involved the tipping of the chip load from the terrain chipper into the bunk of the chips forwarder. The drive full element included the time taken to drive back to the loading area with the wood chip. The unloading element involved the tipping of the wood chip load at the forest roadside. Waiting happened frequently for the chips forwarder, this element comprised of any time where the chips forwarder was waiting for the terrain chipper to complete filling its bunk before loading could commence. The delay element included any other time which was not applicable to any other element.

An important distinction must be made when assessing the productivity of the chips forwarder. While the chips forwarder is waiting for the terrain chipper, the system is still in a productive state. Because the terrain chipper and chips forwarder interact with each other, the system's productivity can only be investigated through discrete event modeling techniques, which will be explored in chapter 7. While the chips forwarder is waiting, it can be thought of as being productive.

The unit of productivity for the chips forwarder in this section is cycles/hour. The chips forwarder is designed to accept a full load from the terrain chipper bunk. Therefore, the productivity of the chips forwarder is directly related to the output of the terrain chipper. Again, the productivity of the system as a whole must be determined, as productivity figures for one machine are meaningless without the other. The machine rate calculations for the chips forwarder was estimated using the method described by Miyata (1980), and is detailed in the table 6.7 below. Regression analysis using the Minitab 16 statistical software package was used to investigate the relationship between cycle time and extraction distance.

Table 6.7: Machine rate assumptions for the chips forwarder

Rate	Unit	Amount
Initial Investment	Euro	425000[a]
Machine Power	kw	210[b]
Salvage Value	Euro	85000[c]
Economic Life	years	6[c]
Scheduled Operating hours	hrs/year	2000[c]
Utilisation Percentage	%	70[d]
Productive Machine Hours	hrs/year	1400
Interest Rate	%	8.5[c]
Insurance and tax rate	%	4[c]
Repair and Maintenance	% of depreciation	100[c]
Depreciation	Euro/year	56666
Average Yearly Investment	Euro/year	283333
Interest	Euro/year	24083
Insurance and Tax	Euro/year	11333
Maintenance and Repair	Euro/pmh	40.5
Fuel Consumption Rate		0.062[c]
Cost of litre of fuel		0.92[c]
Fuel	Euro/pmh	11.98
Lubrication Consumption Rate		0.35[c]
Lubrication	Euro/pmh	4.2
Labour	Euro/smh	15.5[c]
Benefits	Euro/smh	5.64[c]
Labour	Euro/pmh	22.1
Benefits	Euro/pmh	8.1
Overheads %	%	5[c]
Operating Profit %	%	9[c]
Ownership cost per SMH	Euro/smh	46.0
Ownership cost per PMH	Euro/pmh	65.8
Operating cost per PMH	Euro/pmh	86.8
Operating cost per SMH	Euro/smh	60.8
Overheads per SMH	Euro/smh	5.3
Operating Profit Per SMH	Euro/smh	10.1
Total Rate per SMH	Euro/smh	122.3
Total Rate per PMH	Euro/pmh	174.7

6.3 Results and discussion

6.3.1 Motor manual time consumption analysis

The duration of the motor manual felling time study lasted for a total of 86528 productive centimins, which equates to 14.41 hours. The breakdown and summary statistics are detailed below in table 6.8. Between 88 and 288 cycles were captured on each site (858 cycles in total). The minimum time to harvest a tree was 16 centimins. The maximum observed was 503 centimins. Overall, across the five sites, the mean time taken for a cycle was 118 centimins, which equates to 1.18 mins.

Table 6.8: Summary of motor manual time study on each site

Site	Duration (productive centimins)	No. of Cycles	Mean productive time per cycle (centimins)	Max productive time in a cycle (centimins)	Min Productive time in a cycle (centimins)
Abbeyfeale	15365	178	86	269	16
Ballybofey	22899	288	80	264	26
Bweeng	14944	100	149	503	20
Toormakeady	15762	204	77	188	23
Woodberry	17558	88	200	687	36

The time consumption analysis for each site is presented in figure 6.1. The least time consumed on each site was the urea time element, which was in the region of 12% to 14%. The down time element was observed as taking between 20% and 24% on four of the sites, while on the Woodberry site it was remarkably higher at 43%. The higher time experienced on the Woodberry site was possibly due to the trees being the largest in the study. The fell element consumed between 21% and 36% of the time. The select time element was the most variable between sites, where it consumed 26% of the time on the Woodberry site, and 42% on the Toormakeady site.

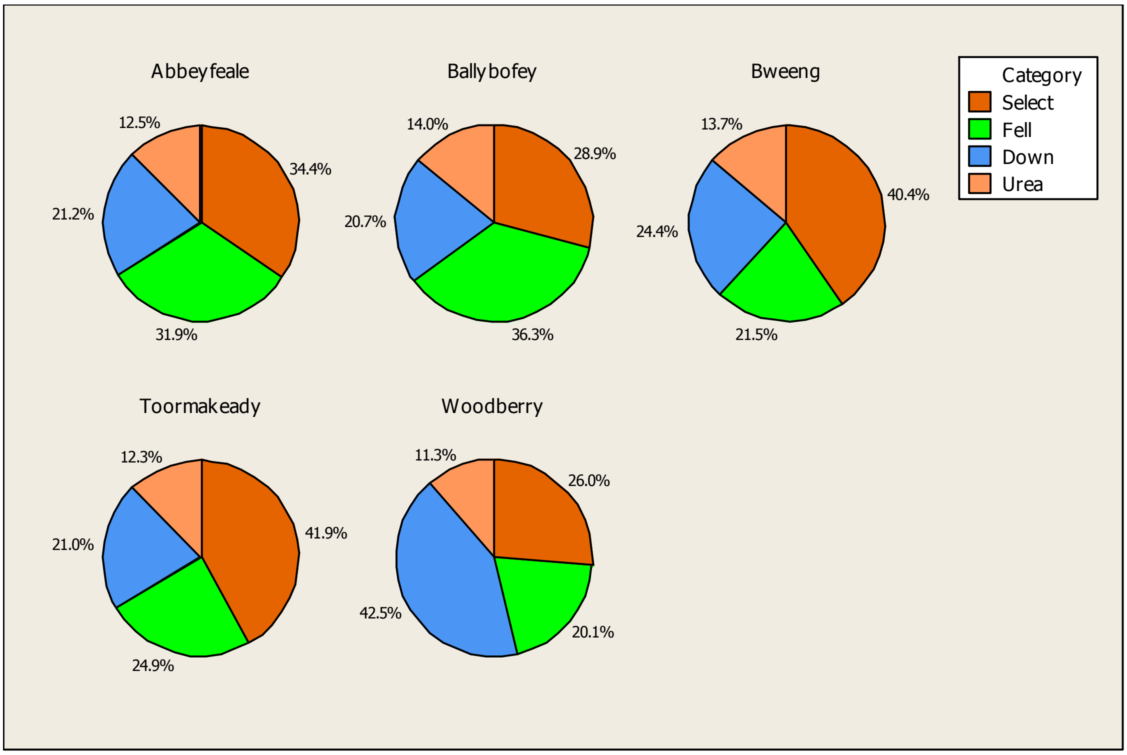


Figure 6.1: Time consumption of chainsaw harvesting of whole trees as observed during the study

Unfortunately, the productivity assessment of the whole tree felling by chainsaw can only be applied as a fixed value. It cannot be used with the taper and dbh to height models in the same way the CTL harvesting machines or roadside chippers have been. The data only describes a mean productive time per tree. The productive time per tree is estimated as 118 centimins (1.18 minutes). Other studies have observed similar results with other figures: Kofman and Kent (2007) observed a productive time of 41 centimins per tree, whereas Spinelli and Magagnotti (2010) developed equations which, using a 60% utilization percentage, predict a productive time of 91 centimins for a tree with a dbh of 10 cm, and 360 centmins productive time for a tree with a dbh of 20 cm.

The thinning as prescribed to the CTL harvesters in chapter 5 was a line and selection thinning consisting of a removal density of 32% from a total stocking of 2346 stems per hectare. In the line thinning, 1 line in 7 was removed. This is the portion of the crop that would be harvested by the motor manual felling. This represents 14.3% of the total stocking, 335 trees. Using the productive time per tree, the time to line thin one hectare is estimated as 6.59 productive hours. Applying the machine rate per productive machine hour of €50.2, this estimates the cost of the line thinning using motor manual felling as being €330 per hectare.

6.3.2 Feller buncher time consumption analysis

The feller buncher was trialled on two sites; Frenchpark and Swan. The total duration of the feller buncher time study lasted for a total of 57743 centimins, which equates to 9.62 hours. A total of 786 cycles were captured during the study. Table 6.9 details the basic statistics for each site.

Table 6.9: Descriptive statistics of the feller buncher time study

Site	Duration (centimins)	No. of Cycles	Mean productive time per cycle (centimins)	Max productive time in a cycle (centimins)	Min Productive time in a cycle (centimins)
Swan	32333	422	33	831	6
Frenchpark	25410	360	38	193	7

The time consumption analysis of the feller buncher is detailed in figure 27 below. The moving and selection elements took up roughly half of the time. The fell 1 element consumed 8% of the time on the Swan site, and 11% on the Frenchpark site. A large proportion of the time, 37%, was attributed to delays on the Swan site, while this was much less, 9%, on the Frenchpark site. A similar portion of time on both sites was consumed by the down element, 20% on the Swan site, and 27% on the Frenchpark site. The fell 2 element, which involved the felling the second tree in an accumulation, only accounted for 0.7% to 1.5% of the time in the study. Further analysis shows that very few cycles accumulated more than 1 tree. Of the 422 cycles observed on the Swan site, only 18 cycles accumulated 2 trees, and of the 360 cycles observed on the Frenchpark site, only 8 cycles accumulated 2 trees. This equates to a mean of 1.042 trees per cycle on the Swan site, and a mean of 1.022 trees harvested per cycle on the Frenchpark site. The average values between the two sites are 36 centimins per cycle, with an average of 1.032 trees harvested per cycle.

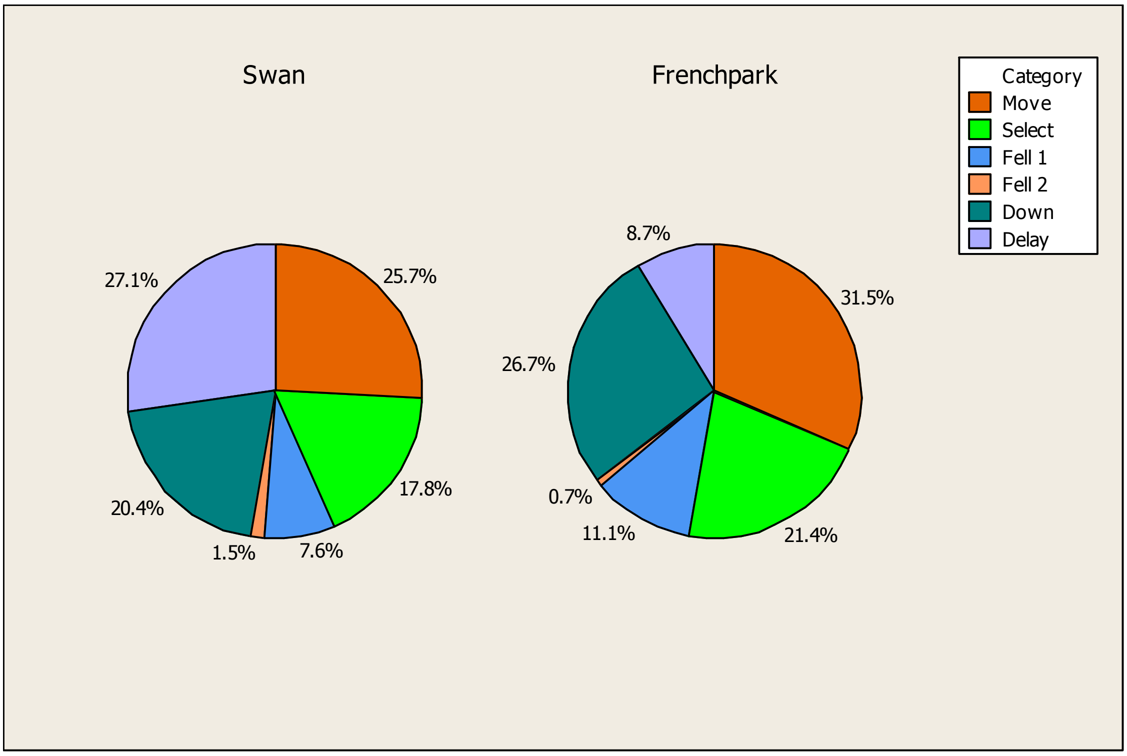


Figure 6.2: Time consumption analysis of the feller buncher as observed during the study

Similar to the chainsaw felling, the feller buncher productivity was assessed as a fixed value. Applying this productivity to the same prescription as the CTL harvester, the fellerbuncher will remove 17.8% of the stems. The total removal density is 32%, the chainsaw felling removed 14.3% in the line thinning. The remaining selection represents 17.8%, 415 trees. The average cycle time is estimated 36 centimins, which equates to 166 cycles per hour. On average, 1.032 trees were harvested per cycle, which estimates the productivity of the fellerbuncher as 177 trees per hour. Using the selection thinning density of 415 trees per hectare, this estimates a productive time per hectare of 2.34 hours. The cost per hectare can then be estimated by applying the machine rate per productive machine hour of €112.4, which gives a cost for selection thinning with a feller buncher of €264 per hectare. Spinelli *et al*. (2007) studied a feller buncher operating in a mixed Pine, Birch and Spruce forest, and observed a average productivity of 260 trees per PMH. The results published by Spinelli *et al*. are not too dissimilar to the data used in this study, verifying that the data is of sufficient quality for this study.

6.3.3 Time consumption analysis of the Silvatec terrain chipper

The Silvatec terrain chipper was trialed on four sites. Before any relation between productivity and piece size, it was necessary to identify if any site effect was present. The Minitab 16 statistical package was used to perform an analysis of covariance (ANCOVA) in a general linear model (GLM). The analysis was uses to show the significance of any site effect on productivity when the effect of piece size was taken into account. The ANCOVA results are detailed in table 43. The data shows that the piece volume has a significant effect (p value 0.000), while site does not when piece size is adjusted for (p value 0.44). Analysis was carried out with an alpha level of 0.05. The results are detailed in table 6.10 below.

Table 6.10: Analysis of covariance for the Silvatec terrain chipper time study data

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mean piece vol. (m3)	1	59797	46623	46623	27.21	0.00
Site	3	4772	4772	1591	0.93	0.44
Error	28	47974	47974	1713		
Total	32	112543				

The time consumption analysis of the terrain chipper during the study is detailed in figure 6.3 below. The study captured 33 complete cycles, a total of 8.25 hours. The results show that the chipper was actively chipping 55% of the time, and unloading into the chips forwarder took 10% of the time. Infrequent moving of the chipper, between lines etc. consumed 13% of the time. Delays accounted for 22% of the time. The waiting time element is not included here, as this is a direct cause of the chips forwarder, and will be modeled in chapter 7.

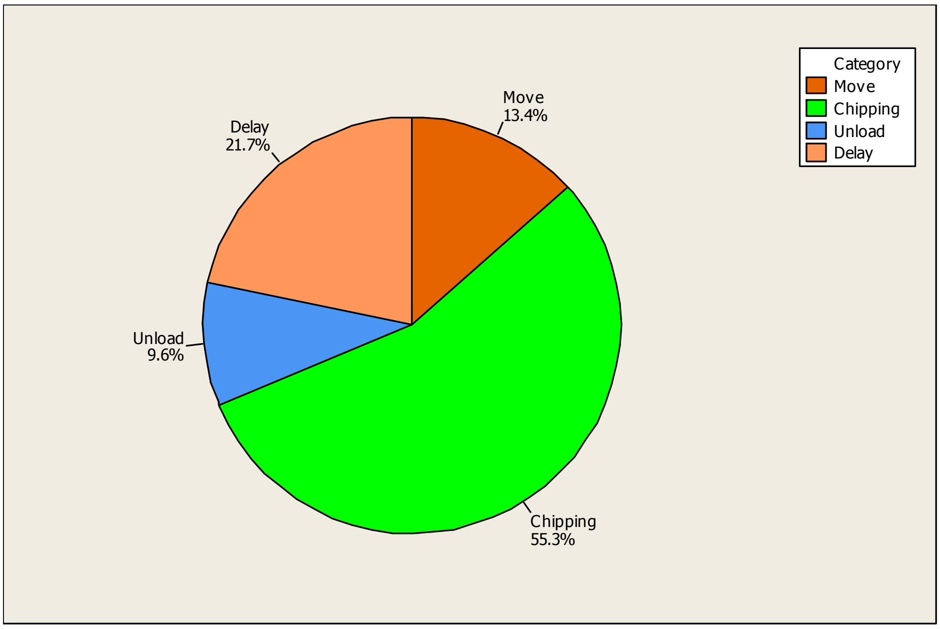


Figure 6.3: Terrain chipper time consumption as observed during the study

Table 6.11 below details the individual cycle results recorded during the terrain chipper study. The wait time (time spent waiting for the chips forwarder) is not included as it is caused by the machine interaction, and will be modeled in chapter 7. The mean bulk density of the wood chip was 291 kg/m^3, and the mean moisture content observed was 47%. The mean bulk density of dry matter was estimated at 154 kg/m^3. This gave the Silvatec terrain chipper a delay free productive time range of between 61 and 301 centimins per m^3.

Table 6.11: Individual cycle results from the terrain chipper study

Site	Bulk density (kg/m3)	Moisture content %	Bulk density of dry matter (kg/m3)	Bulk vol. to solid vol. conversion factor	Solid vol in bunk (m3)	Mean piece vol. (m3)	Productive time per m3 solid
Abbyfeale	262	43	149	0.332	5.65	0.17	183
Abbyfeale	340	55	155	0.346	5.88	0.14	217
Abbyfeale	263	44	149	0.333	5.66	0.14	301
Abbyfeale	273	45	150	0.335	5.70	0.11	287
Abbyfeale	262	43	150	0.336	5.71	0.16	177
Abbyfeale	267	43	152	0.340	5.78	0.14	283
Abbyfeale	249	41	147	0.328	5.58	0.12	202
Abbyfeale	231	36	147	0.329	5.59	0.11	294
Abbyfeale	258	42	150	0.337	5.72	0.15	192
Ballybofey	291	50	145	0.324	5.51	0.09	210
Ballybofey	316	55	143	0.320	5.43	0.10	172
Ballybofey	282	51	139	0.311	5.28	0.09	249
Ballybofey	279	51	136	0.304	5.16	0.11	284
Ballybofey	291	51	142	0.317	5.39	0.09	188
Ballybofey	280	49	142	0.317	5.39	0.39	71
Ballybofey	272	49	139	0.311	5.29	0.11	219
Ballybofey	280	48	145	0.325	5.52	0.10	228
Ballybofey	275	48	142	0.318	5.41	0.09	218
Ballybofey	264	45	145	0.324	5.51	0.09	254
Ballybofey	282	50	142	0.317	5.39	0.08	299
Toormakeady	296	49	152	0.340	5.78	0.12	290
Toormakeady	301	49	152	0.341	5.79	0.10	197
Toormakeady	401	49	204	0.456	7.76	0.14	213
Toormakeady	299	46	161	0.361	6.13	0.38	61
Toormakeady	292	46	157	0.352	5.99	0.13	229
Toormakeady	311	49	160	0.358	6.08	0.11	200
Woodberry	332	45	181	0.405	6.88	0.18	131
Woodberry	305	43	173	0.387	6.58	0.16	181
Woodberry	316	47	166	0.372	6.32	0.18	229
Woodberry	327	49	168	0.376	6.40	0.22	184
Woodberry	295	46	159	0.357	6.06	0.26	173
Woodberry	316	48	165	0.368	6.26	0.28	158
Woodberry	301	42	174	0.390	6.64	0.37	151

6.3.4 Silvatec terrain chipper productivity model development

The Minitab 16 statistical package was used to investigate the relationship between the independent variable of piece size and the delay free cycle time per m^3. However, because the loading element is an interaction of two machines, it was modeled as a separate entity. If the loading time was included in the linear regression, this time element would be accounted for twice when estimating the system productivity. This will be discussed further in chapter 7.

The unloading time for the terrain chipper was analysed using the stat fit statistical software. An Anderson Darling test found the data to fit the lognormal distribution significantly at an alpha level of 0.05. The lognormal parameters were found to be μ=0.254 and σ=0.408 (data in minutes).

The productivity of the terrain chipper according to piece size is displayed in figure 6.4. The regression was found to be statistically significant at an alpha level of 0.05. The R^2 of the model is 0.44. No other variables were measured that could improve the model. The equation of the line is given as:

$$Silvatec_t = 249.2 - 434.2 Piece_{vol}$$

Where:

$Silvatec_t$= delay free cycle time of the terrain chipper (not including loading) in centimins per m^3 solid volume.

$Piece_{vol}$= solid volume in cubic metres of the mean tree in a load

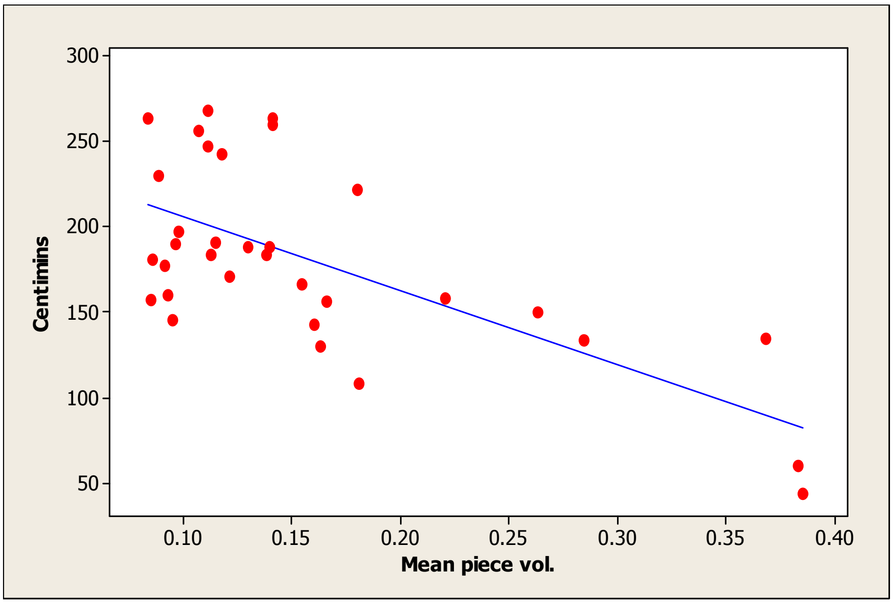


Figure 6.4: Scatterplot of Silvatec cycle data (not including loading) with a regression line describing the relationship between mean piece volume and time chipping per load

<u>6.3.5 Time consumption analysis of the Silvatec chips forwarder</u>

The time consumption for the chips forwarder is detailed in figure 6.5 below. The study captured 53 cycles of the chips forwarder, a total of 26.5 hours. The large wait time may not be truly representative of the waiting for the chipper for all cycles. There may be a number of confounding factors; whenever the chipper is in a delay state, the forwarder will experience a long waiting element. Also, no delay was observed for the chips forwarder as the driver was in constant communication with the chipper, and during the study, managed to deal with any minor maintenance or personal issues during a waiting period. The drive empty accounted for 17% of the study time. The loading time was relatively small, at only 3%. Similar to the CTL forwarder, the drive full time was shorter than the drive empty time, at 14%. This is for the same reason as experience in the CTL forwarder study; the forwarder driver observed the site and made decisions on the journey into the forest about the best extraction route to take on the way out once loaded. After loading it was only a matter of driving directly along this route. Unloading at the roadside consumed 4.5% of the total time.

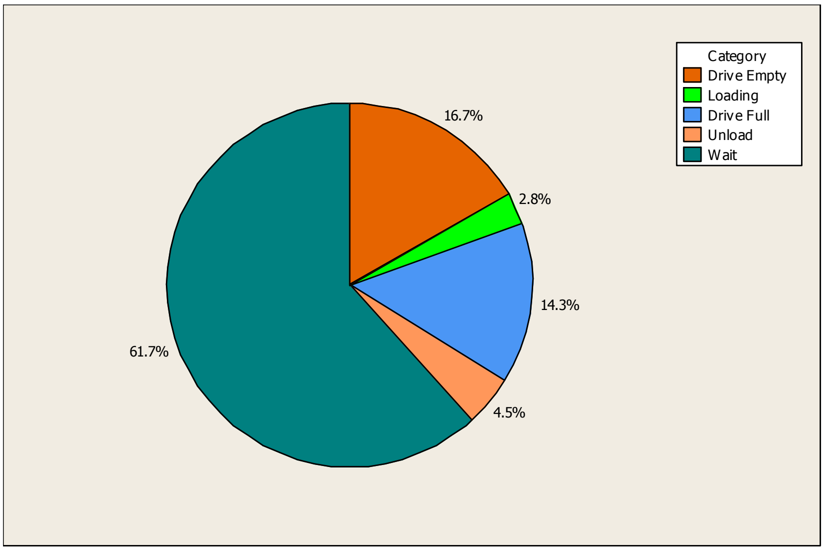


Figure 6.5: Time consumption analysis of the chips forwarder as observed during the study

Regression analysis was performed using the Minitab 16 statistical software package. The analysis investigated the relationship between mean extraction distance and productive time per cycle. As per the terrain chipper, the loading time for the chips forwarder was not included in the analysis. Nor was the waiting time, as this element is a direct response to the machine interactions, and will be modeled in chapter 7. The scatter plot of the data is represented with a fitted regression line in figure 6.6.

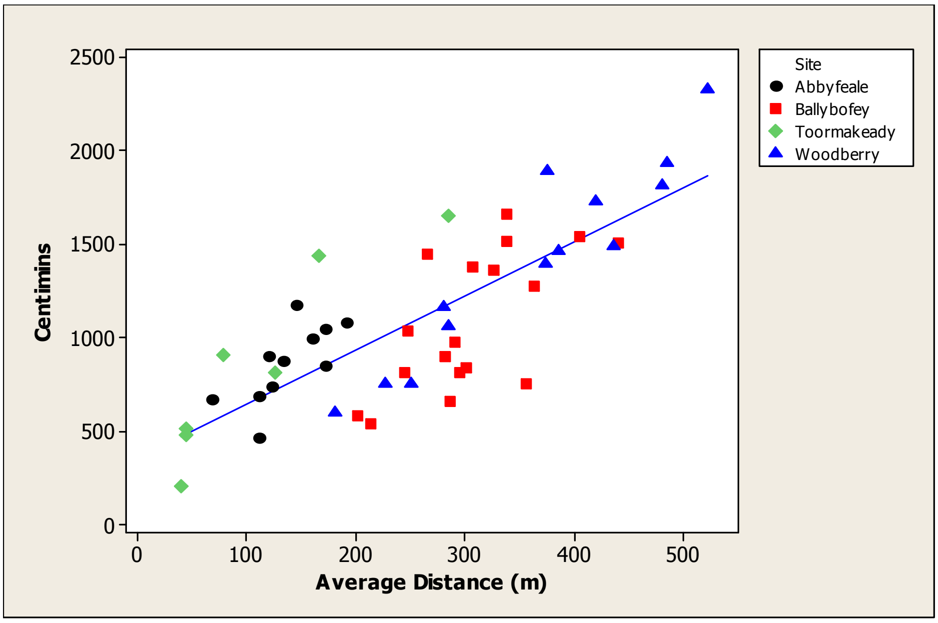


Figure 6.6: Scatterplot of chips forwarder cycle time versus average extraction distance with regression line describing the relationship between average distance (m) and time per load

The regression analysis shows a significant relationship between average distance and cycle time, which has a P value of 0.000. The R^2 is reported as being 63.5% and the R^2 adjusted as being 62.8%. The fit statistics for the regression are displayed below in table 45.

Table 6.12: Fit statistics for the chips forwarder model

Predictor	Coefficient	Standard Error	P
Constant	353.25	90.75	0.0000
Average Distance	2.9004	0.3205	0.0000

The model takes the simple linear equation:

$$Chips\ Forwarder_t = 353.25 + 2.9004 Average\ Distance$$

Where:

$Chips\ Forwarder_t$= delay free cycle time (centimins) of the chips forwarder elements: drive empty, drive full and unloading.

$Average\ Distance$ = Average extraction distance in metres.

6.4 Concluding Remarks

Models were developed to predict the productivity of the terrain chipper and chips forwarder operating in Sitka spruce first thinning in Ireland. However, the machines operate in tandem together and the productivity of the machines influence each other. For the system productivity to be assessed, discrete event modeling must be used, which will be discussed in chapter 7. The machine rate per scheduled hour for the machines is €176 per hour, and €122 per hour respectively. This estimates the overall system rate per scheduled machine hour at €299. The whole tree harvesting productivity figures were asses as a mean figure per hectare. The motor manual cost has been estimated at €330 per hectare. The feller buncher cost has been estimated at €264 per hectare.

Chapter 7: Discrete event modelling of the Silvatec terrain chipping system

7.1 Introduction

Harvesting systems where machines operate independently are described sufficiently by deterministic models, for instance, a harvester and a forwarder may operate on completely separate occasions and so an independent model for each machine will describe the system well. This is the basis for all the machine productivity models developed in this dissertation so far. However, in a harvesting system where the machines interact with each other, discrete event modelling will provide more accurate results (Bjorheden, 2008 as cited in, Spinelli and Picchi, 2009)

All operational systems are stochastic, whether or not the models describing them incorporate this. The productivity model for the harvester developed in chapter 4 is a deterministic static model. The system has random variability around the model, but the model describes the system average through a linear function. If a stochastic element is added to the model to describe this variability, the model is no longer deterministic, but is still static, as it does not matter when the random events occur. Only when a model uses time as a variable, does it become a dynamic model. A dynamic model can also be deterministic, if the model is simply projecting an average over time (Leemis and Park, 2006). A dynamic and stochastic model is a model where the point in time when a random event occurs has consequences. This can be described through discrete event simulation.

Discrete event simulation is the modelling of systems where variables change at discrete points in time only, as apposed to continuous systems that change constantly over time. However, it is possible to model continuous systems with discrete event models (Banks and Carson, 1984). An easy way to make the distinction between discrete and continuous modelling is an analogy of a tank filling with water; as the water is filling the tank, the state of the tank is continuously changing until full. If this was to be described by discrete events, the tank would have three states; empty, filling, and full. This can also be applied to forest operations. For example, the movement of the forwarder along an extraction rack is a continuous event, however, if forwarder movement is represented abstractly as a single state, a discrete event can describe this.

Banks and Carson (1984) give an excellent description of the difference between discrete models and the static type models developed thus far in this dissertation.

"Simulation models are analysed by numerical rather than by analytical methods. Analytical methods employ the deductive reasoning of mathematics to "solve" the model. For example, differential calculus can be used to determine the minimum-cost policy for some inventory models. In the case of simulation models, which employ numerical methods, models are "run" rather than solved; that is an artificial history of the system is generated based on model assumptions, and observations are collected to be analysed and to estimate the true system performance measures".

To develop a discrete event model, the discrete events must be fitted together in a series of logical conditional statements that mimic the real world system. The form of the conditional statements is given by Pidd (1989) as:

If [condition] *then* [contingent actions]

There are a number of purpose built computer programs for developing discrete event models. These allow for fast simulation time and ease of build. The programs also allow for the development of models without first requiring a broad knowledge of computer programming. Understanding the conditional argument form set out by Pidd (1989) and stochastic probability distributions is sufficient to build a model in the Simul8 software package.

Discrete even modelling has been used to model forest harvesting and forest supply chain systems over the last few decades. Hogg *et al.* (2009) used the commercial discrete event simulation software Arena 9 to model the supply chain of saw logs in South Africa. Time studies of harvesting, extraction, processing, and loading machines were taken, and the data used in the model. The systems trialled used skidders to extract whole trees to the landing, where processors crosscut and delimbed the trees. Loaders then placed the logs onto transport trucks. With all these machines depending on each other to operate, the authors were able to use discrete event modelling to carry out cost comparisons of the optimal number of machines to use in the system. Väätäinen *et al* (2006) used discrete event modeling to investigate the competitiveness of harwarder machines in cut to length operations in Finland. Harwarders are machines that both work as a harvester and forwarder, and so the system uses only one machine. The authors took data which had been previously collected in other studies, and used discrete event simulation to identify conditions that were suitable for the harwarder machines. The authors used the WITNESS simulation software. Cavallii *et al* (2010) studied the effect of the forest road network on energy wood production in Italy, also using the WITNESS discrete event simulation software. The authors first performed detailed productivity studies on the extraction and processing of trees at the landing. Using discrete event simulations, they were able to investigate the impact of the forest road network, and also the buffer area (space available for material to accumulate) around the processors, on the productivity of the system. The buffer area of a harvesting system was also a concern for a study carried out by Asikainen (2001) The study investigated barge transportation of logs from stands being harvested on small islands in Finland. Forwarders extracted logs from the forest, and unloaded them onto barges on the water system. At the unloading point, buffer rafts were used so that the forwarders could keep extracting when the barges were in transit to the mill. Discrete event simulations were used to identify the number of barges needed to maintain a productive system at increasing transport distances, as once the buffer raft was full; the forwarder could no longer operate. Talbot and Suadicani (2005) used discrete event modeling to compare terrain chipping systems under different conditions. Two systems were compared: a SOLO system where the terrain chipper worked independently chipping and extracting to the landing, and a DUO system where woodchip was transferred to a chips forwarder for extraction. Talbot and Suadicani used both time study data and machine specifications for the machine productivities, modeling the system in the SAS statistical software package.

The objective of this chapter was to estimate the productivity of the Silvatec terrain chipping system in Sitka spruce first thinnings in Ireland. The study aimed to estimate the productivity at different levels of two factors: the mean dbh of a stand, and the mean extraction distance.

7.2 Materials and methods

The discrete event simulation software *Simul8* (Simul8 Corporation, 2010) was used to model the system productivity of the terrain chipper and the chips forwarder. Simul8 has a graphical user interface allowing models to be built up without the user needing any programming knowledge. If required, the visual logic code can be edited by the user, but in the case of the model built in this study it was not needed. The Simul8 software uses icons (called work centres) that are selected and dragged into a simulation area and linked together in the logical order of the real world system being modelled. Work items (units of work) flow into the model from a work entry point, and flow out at a work exit point. Each work centre has parameters that are set by the user to define how and when work passes through the work centre, e.g. the time taken for a unit of work to pass through the work centre. The values of the parameters can be fixed, random, follow a probabilistic distribution or formula. Values can also be sampled from external sources such as databases and spreadsheets. Figure 7.1 below displays the simulation window of the model built in this study. It consists of three main work centres: chipper, loading interaction, and forwarder. The other work centres are dummy centres, which are used to control logic in the model.

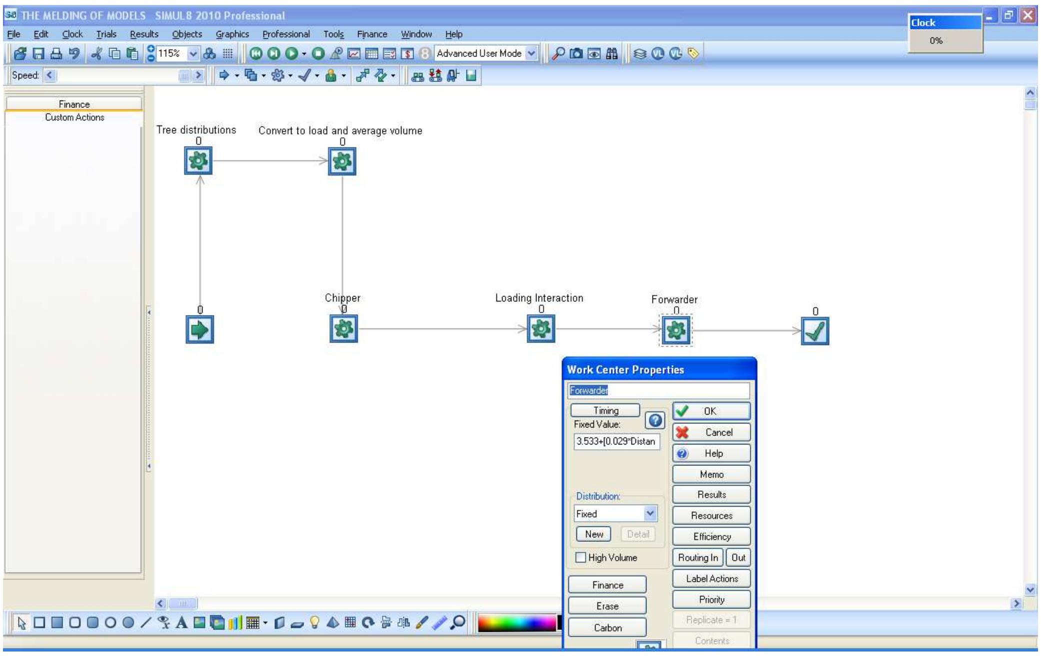
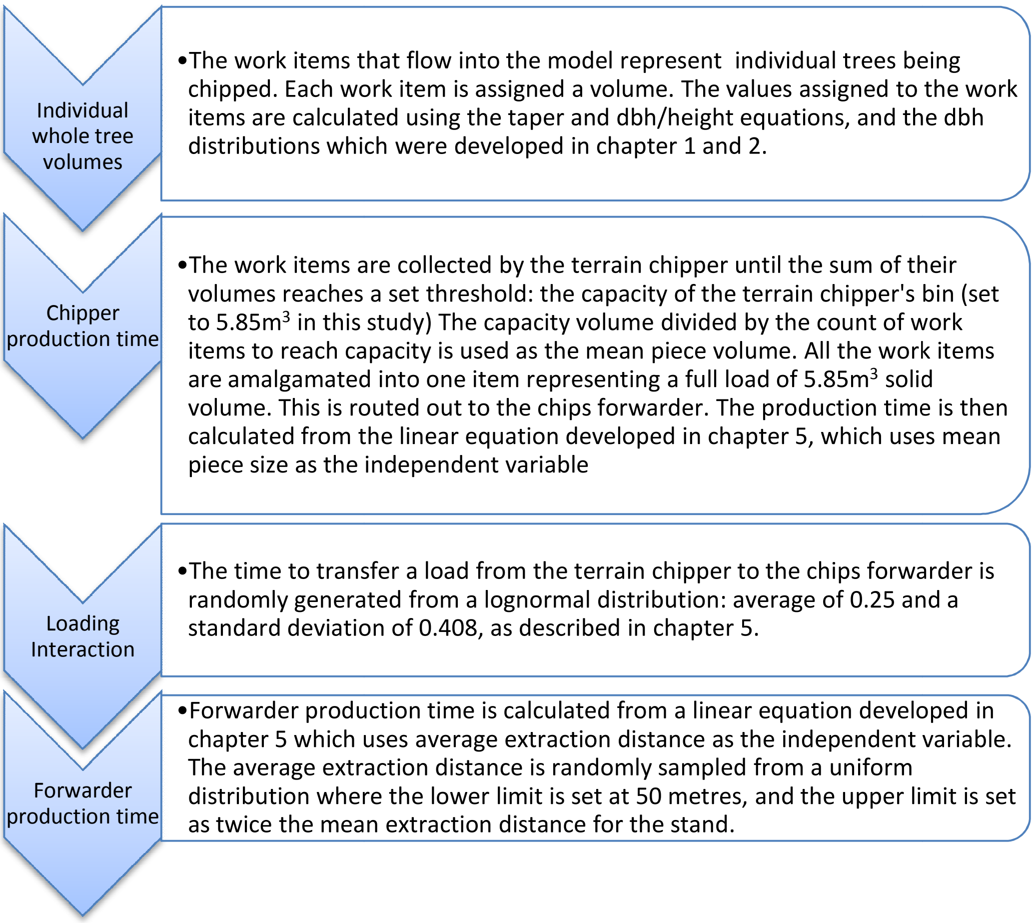


Figure 7.1: Simul8 graphical user interface

The model built in this study uses the production equations developed for the terrain chipper and chips forwarder in chapter 6, and the whole tree volume datasets simulated in chapter 3. There are five input elements controlling the model:

- The individual whole tree volumes
- The chipper production time
- The transferring time between the chipper and forwarder
- The distance of extraction to the roadside
- The chips forwarder production time
- Delays

The logic to how the model elements fit together is described below. For each load that the system produces, the following process occurred:



Not all elements in the real world system can operate at the same time, and so, rules are implemented so that the model mimics this i.e. the work items cannot move from the chipper work centre until the chips forwarder work centre is ready to accept them, the chipper work centre cannot operate while the loading interaction work centre is operating, and similarly, the forwarder work centre cannot operate while the loading interaction work centre is operating.

Delays are accounted for according to the utilisation percentage of the machines, in this study 70% for both the terrain chipper and chips forwarder. Simul8 uses distributions that are commonly used in manufacturing processing to distribute the delays; negative exponential for the distribution of the delays, and Erlang 2 for the down time. It is also possible to define delay distributions for Simul8 to use, but as there was no extensive investigation into the terrain chipping delays, it was considered best to use the in built system. To correctly account for delays, the work centres were grouped and a delay assigned to the group. This was required as the real world machines were being represented by more than one work centre, and the machine interaction work centre represented both the terrain chipper and the chips forwarder at the same time.

The model was used to investigate the productivity of a Silvatec terrain chipping system under different conditions. Two factors were investigated: the mean dbh of a stand, and the mean extraction distance of a stand. The mean dbh factor had 11 levels: 10 cm to 20 cm inclusive. The Silvatec chipper specifications state that the machine is capable of chipping material up to 35 cm in diameter. The largest dbh as predicted by the dbh distributions in chapter 3 is in the region of 31 cm, and so the Silvatec should be capable of chipping all stems. The mean extraction distance had 10 levels; 100 m to 1000 m inclusive. A full factorial experimental design was constructed in the Minitab 16 statistical program. The design tested the system at every possible combination of the factor levels, 110 combinations. For each combination, 5 replications were made with the Simul8 software using a different random number stream, so that the results could be compared statistically. The run time for the model was 110 hours for each replication; the warm up period was 10 hours, and the results collection period was 100 hours. A warm up period was used as it allows the model to reach a stable state before results are collected.

7.3 Results and discussion

The results from the simulation experiment show that both factors: mean dbh of the stand, and mean extraction distance of the stand, caused statistically significant effects on the response (m^3 per hour). The analysis also shows that the mean extraction distance and mean dbh have an interaction effect on the productivity. Table 7.1 details the results.

Table 7.1: Analysis of variance of the full factorial design experiment of the Silvatec terrain chipping system

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mean dbh	10	178.68	178.68	17.87	233.41	0.000
Mean extraction distance	9	10069.14	10069.14	1118.79	14614.7	0.000
Mean dbh*Mean extraction distance	90	312	312	3.47	45.29	0.000
Error	440	33.68	33.68	0.08		
Total	549	10593.52				

An interaction plot of the factors is displayed in figure 7.2. Each data point in the graph represents the mean of 5 replications of each factor combination. The graph shows that mean dbh has an effect on productivity at short extraction distances, but as distance increases, the difference due to mean dbh lessens. This is because, as the extraction distance increases, the terrain chipper reaches its capacity of 5.85 m^3 in its bin, and cannot chip any longer until the load is transferred. At short distances the chips forwarder is ready for loading by the time the chipper is full. Tree size affects the system productivity under these conditions, as the faster the chipper can fill its load, the faster the system as a whole is operating. At longer distances, the chipper must stop once its capacity is reached, and wait for the chips forwarder to return. Under these conditions, it is solely the forwarder productivity affecting the system, as no matter how productive the chipper is, it must stop and wait for the forwarder to return. It is also worthy to note, that in the graph the data points (which represent the mean values of 5 replications) are shown to be merging closer together as extraction distance increases, but the individual data points for each group are actually increasing in variance. An analysis of the data has shown that the standard deviation within each grouping increases as extraction distance increases. This is a response to the system becoming more sensitive to a breakdown or delay cause by one, or both, of the machines. A scatterplot of each individual run is presented in figure 7.3 to illustrate this, and to show the variability of the data in general.

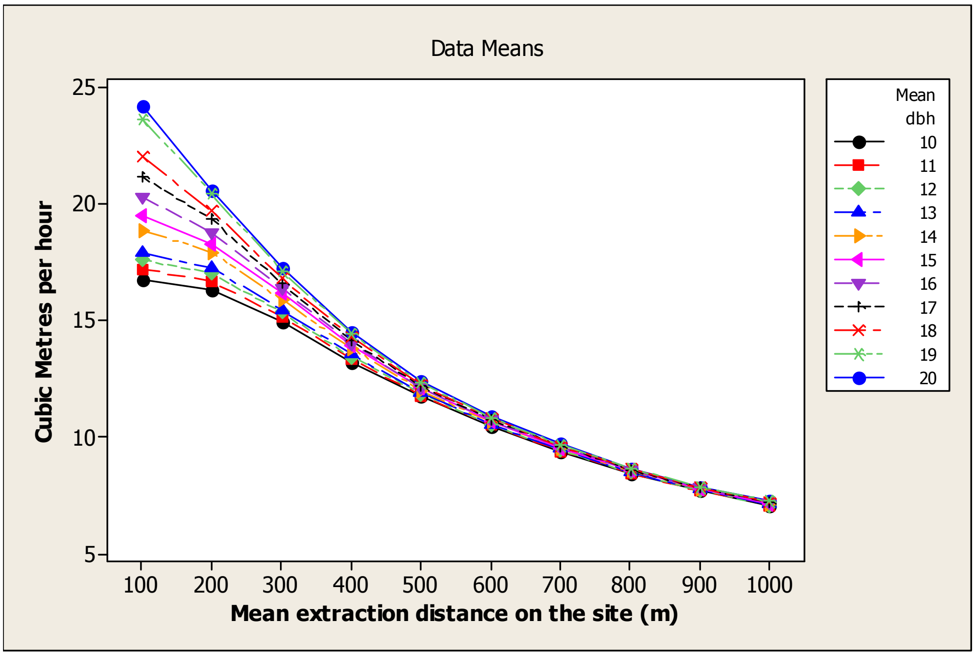


Figure 7.2: Interaction plot of the simulation results for the Silvatec terrain chipping system productivity (m^3 per hour)

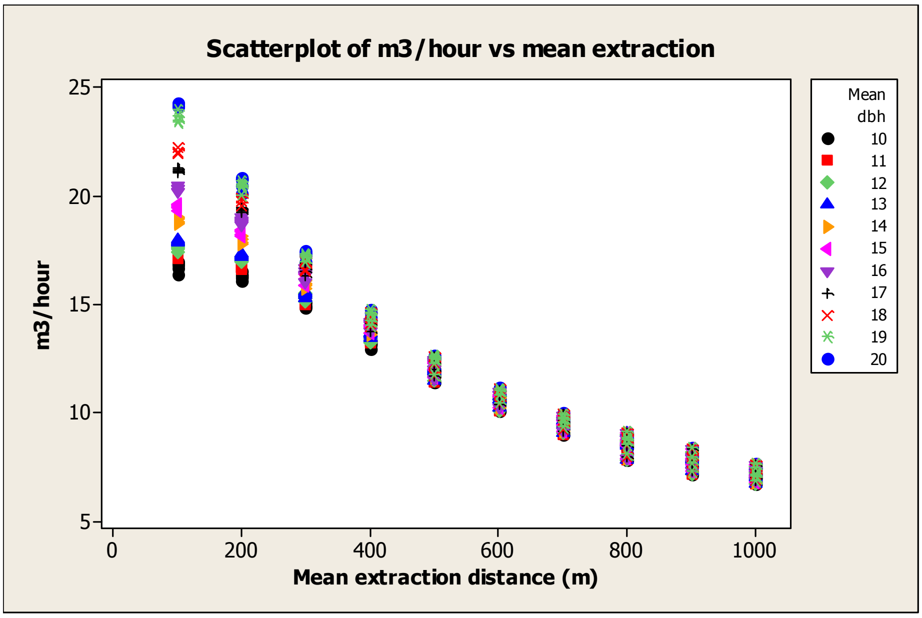


Figure 7.3: Scatterplot of m^3 / hour vs. mean extraction, using the data from each replication from the simulations of the Silvatec terrain chipping system

It is possible for discrete event simulation to capture a wealth of information on a modelled system. Figure 7.4 below illustrates the waiting time experienced by the chipper during the simulations. The data shows that at small mean extraction distances of 100m, the wait time is between 0 and 5%, depending on the mean dbh level. At a mean extraction distance of 500m, the chipper experienced a waiting time of between 20% and 38%. The mean dbh level impacts on the wait time as the faster the chipper is producing chip, the more time will be spent waiting. However, this does not mean any overall difference in the system productivity, as can be seen in the previous graph. This gives an interesting application of the results: if dbh is small, the chips forwarder could chose not to extract to the nearest landing, but instead extract the chip to a more suitable location that offered more space for manoeuvring, or offered better access conditions for haulage vehicles, even if this location was farther away (Spinelli, 2012).

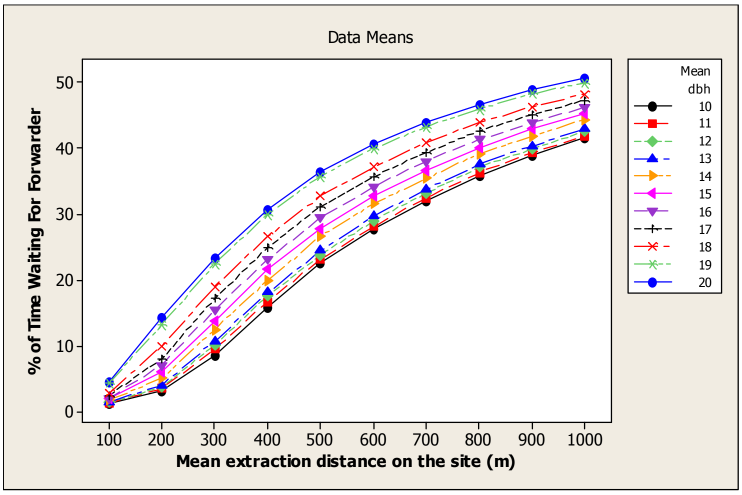


Figure 7.4: Percentage wait time for the Silvatec terrain chipper in the simulation study

Likewise for the forwarder, the wait time percentage is displayed in figure 7.5. As the mean extraction distance increases, the wait time decreases. As the forwarder has more ground to cover, it is not making it back to the chipper before the chipper has reached its capacity. A wait time experienced by the forwarder does not adversely affect the system productivity, whereas a lack of wait time does, as chip production is being stopped.

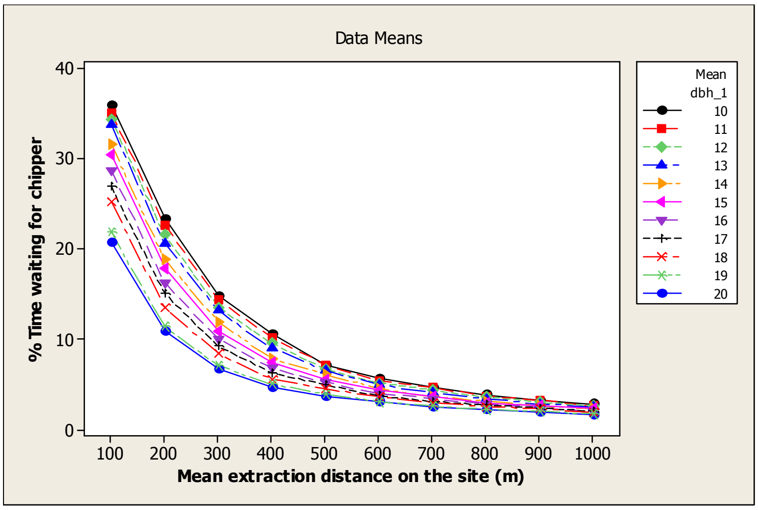
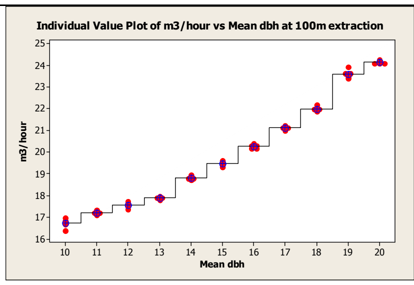
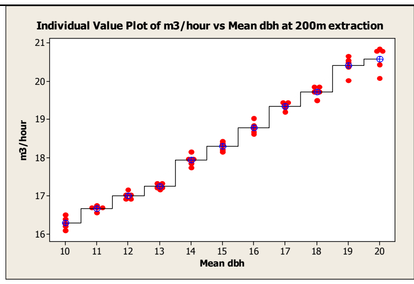
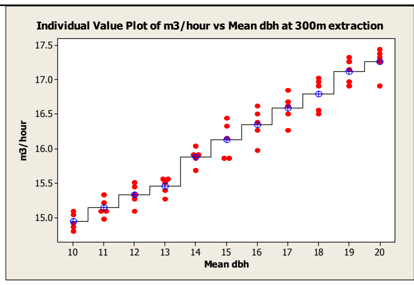
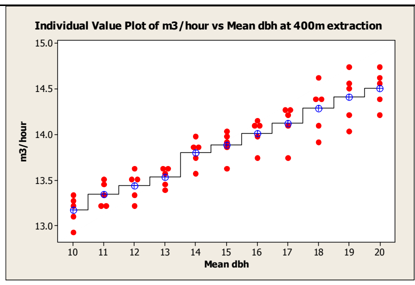
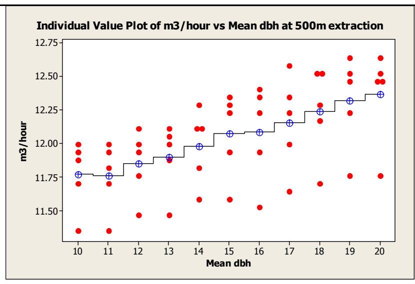


Figure 7.5: Percentage wait time of the chips forwarder waiting for the terrain chipper in the simulation study

To further analyse the results of the system as a whole, an analysis of variance was carried out to identify at what extraction distance the mean dbh level no longer had statistical significance on the productivity. The results of the ANOVA are presented in table 7.2. The results show that mean dbh is no longer statistically significant at a mean extraction distance of 500m or greater.

Table 7.2: ANOVA and individual value plot for m^3 per hour vs. mean dbh at mean extraction distances from 100 m to 500 m for the Silvatec terrain chipping system in the simulation study

Mean Extraction Distance (m)	P Value	R-Squared	Graph
100	0.000	99.78	
200	0.000	99.93	
300	0.000	95.23	

400	0.000	86.14	
500	0.126	34.92	

The machine rate costing for the Silvatec terrain chipper and the chips forwarder that was detailed in chapter 6 was used to estimate a cost per cubic metre of the system. The scheduled machine hour cost was used as the analysis of the system took into account random breakdowns which caused interactions between the machines. The combined scheduled machine hour rate of both machines was used for a system cost per scheduled machine hour of €299.10. The results are illustrated in figure 7.6 below. The cost per m^3 ranged from €12.4 to €17.9 at 100m mean extraction distance, depending on the mean dbh level. At 500m extraction distance, the cost per m^3 ranged from €24.2 to €25.4. Again as per the productivity the mean dbh level had no significant effect at 500m extraction distance or higher. At 1000m mean extraction distance, the cost per m^3 was between €42 and €43. Kofman and Kent (2007) observed a Silvatec terrain chipping system in Ireland at short extraction distances and estimated the average cost to be €11.86 / m^3. This agrees with the predicted costs at short distances in this study, validating the results.

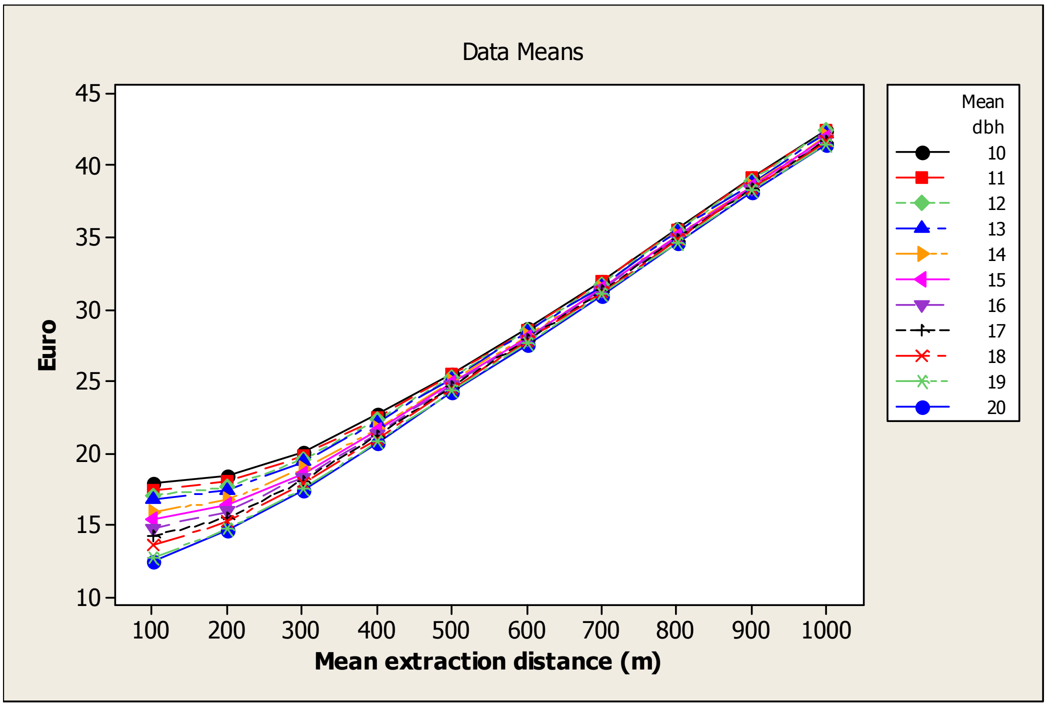


Figure 7.6: Predicted cost per m^3 using the Silvatec terrain chipping system in Sitka spruce plantations at first thinning

7.4 Concluding remarks

In complex systems where machines interact with each other during harvesting, discrete event simulation can adequately model the systems to not only estimate the productivity, but also identify how factors affect the system overall. The results show that productivity of the system increases as dbh level increases, but also decreases as extraction distance increases. The discrete event simulation results have shown that the Silvatec terrain chipping system is expected to operate from €12 per cubic metre to €43 per cubic metre, depending on the tree size and extraction distance. Extraction distance has shown to be the most influential factor on the system, as woodchip production stops if the forwarder has not returned to the terrain chipper before the chipper bunk is full. The outcome of this is that at 500m extraction distance, or greater, tree size no longer has a statistical significant effect on the productivity. This illustrates the vulnerability of the Silvatec terrain chipping system to long extraction distances, which may prevent the system being cost effective on certain sites. This drop off in productivity may overcome by adding a second forwarder to the system. Further development of the discrete event model constructed in this chapter could model the model the effectiveness of adjustments to the system such as this to a high resolution.

Chapter 8: Profit analysis of the harvesting systems

8.1 Introduction

The previous chapters in this dissertation have described parameters that effect first thinning operations in Sitka spuce plantations in Ireland. In this section, the results from the previous chapters will be used to evaluate the profit from three thinning systems:

- CTL harvesting for sale of all roundwood products
- CTL harvesting for sale of sawlog and pallet products, and chipping of pulp products for the energy market
- Whole tree harvesting and terrain chipping of whole trees for sale to the energy market

8.2 Method

To perform the profit analysis, a market price for the products at the forest roadside was required. Teagasc (2012) published the most up to date roundwood timber prices in April 2012. The prices are those as achieved by private forest owners. Table 8.1 details the Teagasc figures.

Table 8.1: Price per m^3 of roadside timber sales as observed in Ireland by Teagasc

Province	Pulpwood	Palletwood	Sawlog
Leinster	27	47	61
Munster	27	45	57
Ulster	25	43	57
Connaught	27	39	57
Average	26	43	58

A market price for woodchip was harder to acquire. SEAI (2011) publish the average market price of woodchip delivered to commercial and industrial end users each yearly quarter. The average figures published for 2011 give a delivered price of woodchip of €0.0299 per KWh (excluding VAT) per oven dry tonne. To use this price, the volume of wood chip produced by the harvesting systems needed to be converted to a unit of energy content. During the productivity studies of the roadside chippers and terrain chipper, woodchip samples were taken and analysed for moisture content using the oven dry method. The results from these are displayed below in figure 8.1 for one and two summers drying.

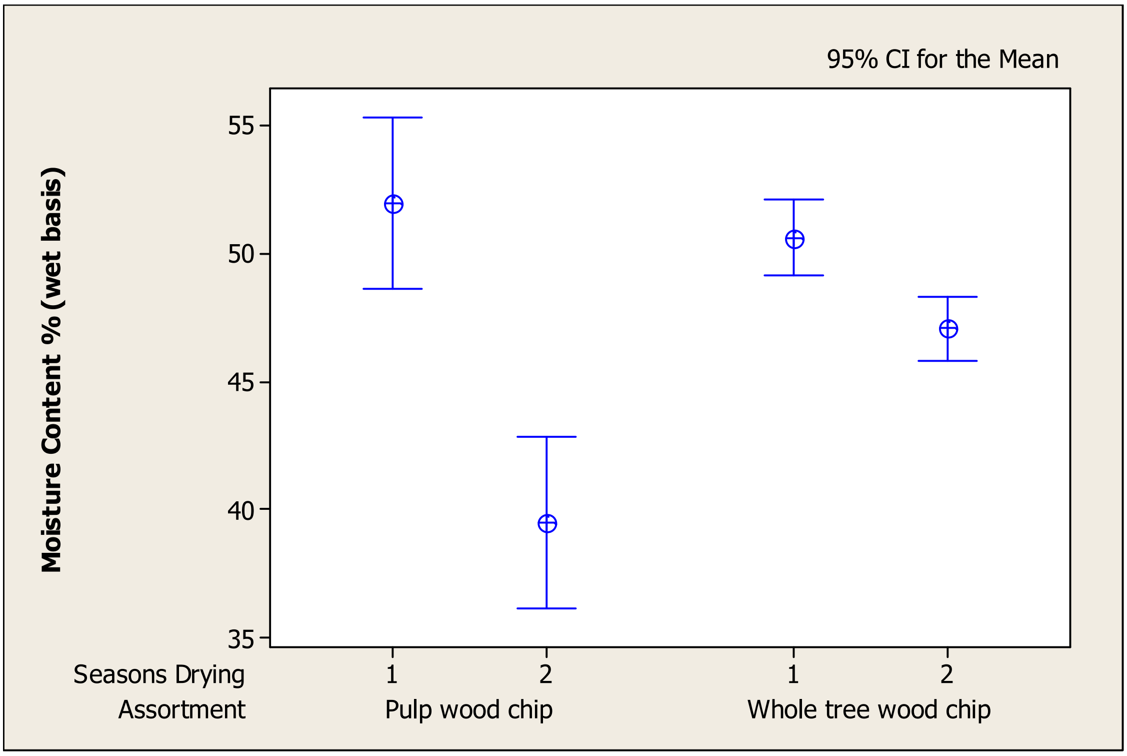


Figure 8.1: Interval plot of moisture content of wood chip products after 1 and 2 seasons drying. Interval represents the 95% confidence interval for the mean

An ANOVA of the data shows that there is no statistical difference between the pulp wood chip and the whole tree wood chip after one season drying. There is however a statistical difference between 1 and 2 seasons drying for both the pulpwood chip and wholetree chip, indicating that seasoning does occur. There is also a statistical difference between the pulpwood chip and the whole tree chip after 2 seasons drying, indicating that the assortments have different drying rates.

Using a formula for net calorific value given by Serup (2005), and the basic density value for Sitka spruce in first thinnings (used throughout this dissertation) of 447 kg/m^3, the energy content per m^3 solid was estimated for each woodchip product. The equation given by Serup is transcribed below:

$$NCV = 19.2 - (0.2164 * MC\%)$$

Where: NCV = net calorific value in GJ per tonne woodfuel from conifer species.

MC% = the moisture content percentage of the wood on a wet basis

The net calorific value was converted to kWh, and the delivered value at the end user for the wood chip products were estimated as:

- €61.73 for pulpwood chipped after 1 seasons drying
- €65.61 for pulpwood chipped after 2 seasons drying
- €62.23 for whole trees chipped after 1 seasons drying
- €63.46 for whole tree chipped after 2 seasons drying

This gives a market price for woodchip delivered to the end-user. In order to be comparable to the roundwood assortments, a value at the forest roadside needed to be estimated. This was done by subtracting a delivery cost of the woodchip from the delivered price. The delivery cost was calculated using the FITPAC model developed by Murphy *et al.* (2010) for UCD and Coillte. The FITPAC model has the ability to predict the cost of chip haulage based on national and internationally published data. A screenshot of the model is displayed in figure 8.2. The inputs to the model were a fuel cost set at €1.569 per litre, operating profit set at 9%, and a travel distance set at 75 km. The travel distance represents the average round trip distance likely to be experienced by a haulier transporting chip to an end-user. Phillips *et al.* (2009) describe the catchment areas for sawmills typically have a haulage distance threshold of 75 km. In this study it is assumed that the distribution of haulage distances is uniform, and that chip hauliers will be making a round trip. This estimates the average total travel distance at 75 km. The FITPAC model returns an estimate of €53.26 per oven dry tonne. Using the basic density estimate of 447 kg/m^3 for Sitka spruce first thinnings, the estimated delivery cost is €23.8 / m^3. This value is not dissimilar to figures published in the UK. The British Department of Energy and Climate Change (2010) report the delivery cost estimates for wood chip (if using the same basic density and haulage distance) of between £26 and £52 (approx. €32 and €64).

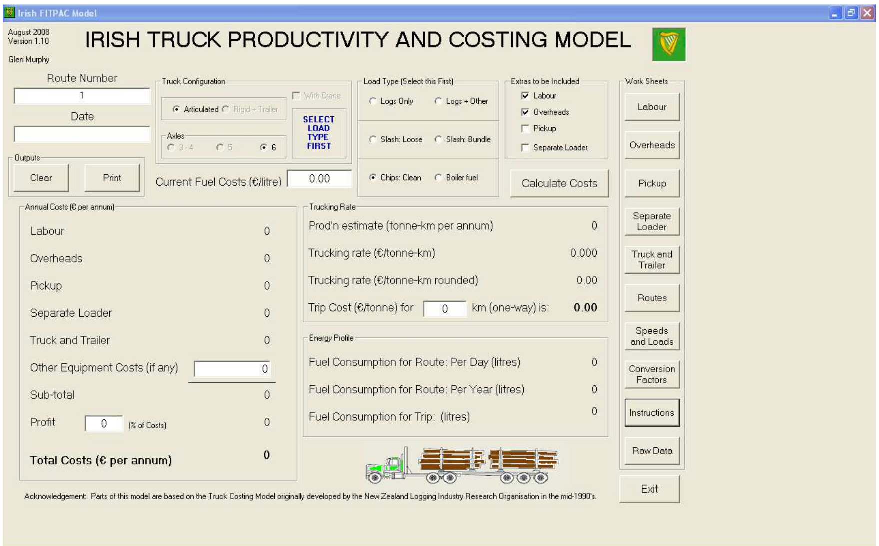


Figure 8.2: FITPAC model user interface

(Murphy et al., 2010)

The delivered to end-user prices for woodchip minus the delivery cost gives the woodchip products a value at roadside of:

- €37.93 / m^3 for pulpwood chipped after 1 seasons drying
- €41.81 / m^3 for pulpwood chipped after 2 seasons drying

- €38.43 / m^3 for whole trees chipped after 1 seasons drying
- €39.66 / m^3 for whole tree chipped after 2 seasons drying

Using the product volumes per hectare estimated in chapter 3, the value at roadside per hectare for each of the harvesting systems is displayed in table 8.2.

Table 8.2: Predicted volumes (m^3) and value (€) per hectare of products at the roadside for Sitka spruce plantations at first thinning

Mean dbh	Large sawlog vol. (m3)	Small sawlog vol. (m3)	Pulp Vol. (m3)	Whole tree vol. (m3)	CTL Products	CTL with chipped pulp after 1 season	CTL with chipped pulp after 2 seasons	Whole trees chipped after 1 season	Whole trees chipped after 2 seasons
10	0	0	3	20	78	114	124	769	793
11	0	0	7	25	182	266	290	961	992
12	0	1	13	36	381	536	582	1383	1428
13	0	2	17	43	528	731	791	1652	1705
14	0	9	24	64	1011	1297	1383	2460	2538
15	0	15	28	78	1373	1707	1806	2998	3093
16	0	22	31	93	1752	2122	2232	3574	3688
17	0	33	36	110	2355	2784	2912	4227	4363
18	0.5	43	39	126	2892	3357	3496	4842	4997
19	8	55	41	153	3895	4384	4530	5880	6068
20	10.8	58	44	161	4264	4789	4946	6187	6385

The time value of money was also taken into account in the analysis. This was required as the wood energy supply chains involve an amount of time between harvesting and chipping. This time has an associated cost as the harvesting costs must be carried over this period. To account for this, the harvesting costs for the woodchip were compounded at a daily interest rate over the seasoning period. An annual interest rate of 8.5% was used (the same value of the rate for borrowing throughout this dissertation). The harvesting costs produced in chapter 4 are estimated for all products. To calculate the fraction of these costs associated to the pulpwood, the total cost was simply multiplied by the pulpwood percentage of the total volume.

8.3 Results and discussion

The profit analysis of the harvesting systems is illustrated in table 8.3. The table displays which harvesting systems are profitable at each combination of mean dbh and extraction distance. The table displays an icon for each system; if the icon is present, then the system has shown to have a positive profit. The following prescription is based on the assumption that if a system returns a positive profit, then it is suitable for use.

The results suggest that:

- At a mean dbh of 10cm and 11cm, no harvesting method is suitable.
- From 12 cm to 13 cm dbh, whole tree harvesting and terrain chipping is suitable, but only at the shorter mean extraction distances of about 300-400m or less.
- At 14 cm mean dbh, only whole tree harvesting and terrain chipping is suitable up to a mean extraction distance of 600 m.
- At 15 cm mean dbh, the CTL systems begin to be usable. The CTL with sale of all roundwood products can be used at very short extraction distances of 100-200 m. The CTL systems with roadside chipping of pulpwood can be used at longer extraction distances of 400-500 m. Whole tree harvesting and terrain chipping are again suitable for use up to 600m mean extraction distance.
- At 16 cm mean dbh, CTL with sale of all roundwood products can be used at mean extraction distances of up to 500m. All other systems are suitable up to mean extraction distances of 700m.
- At 17cm to 20 cm mean dbh, all systems are suitable up to a mean extraction distance of 700 m. CTL with roadside chipping is suitable up to mean extraction distances of 1000m.

CTL with sale of all roundwood products is also suitable up to 1000m mean extraction distance at a mean dbh of 19 cm and 20 cm.

Table 8.3: Prescription for harvesting systems in first thinning Sitka spruce plantations in Ireland

Icons indicate that the system is profitable under the conditions

Mean extraction distance (m)

Mean dbh (cm)	100	200	300	400	500	600	700	800	900	1000
10										
11										
12	4 5	4 5	4 5							
13	4 5	4 5	4 5	4 5						
14	4 5	4 5	4 5	4 5	4 5	4 5				
15	1 2 3 4 5	1 2 3 4 5	2 3 4 5	2 3 4 5	3 4 5	4 5				
16	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	2 3 4 5	2 3 4 5			
17	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3	2 3	2 3
18	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3	1 2 3	2 3
19	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 5	1 2 3	1 2 3
20	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3	1 2 3

1 = CTL harvesting, sale of all roundwood products

2 = CTL harvesting, sale of sawlog and pallet, seasoning of pulp for 1 summer, chipping of the pulp with the Jenz 700 roadside chipper, sale of chip

3 = CTL harvesting, sale of sawlog and pallet, seasoning of pulp for 2 summers, chipping of the pulp with the Jenz 700 roadside chipper, sale of chip

4 = Whole tree felling, seasoning of whole trees for 1 summer, terrain chipping of the whole trees, sale of chip

5 = Whole tree felling, seasoning of whole trees for 2 summers, terrain chipping of the whole trees, sale of chip

The main trend that can be seen from the results is that mean dbh affects the CTL systems more than the whole tree system. The mean extraction distance affects the whole tree system more. The whole tree system has the ability to be used at lower levels of mean dbh than the CTL systems. However, the whole tree system is crippled by extraction distance. Above a mean extraction distance of 700-800 m, the whole tree system cannot be used, regardless of tree size.

For further reference, the predicted profits for each system are presented in tables 8.4 through 8.8. It is also important to note that the machine rate calculations incorporate a 9% profit margin.

Table 8.4: Predicted profit (€) per hectare using the CTL harvesting system with sale of all roundwood products in Sitka spruce plantations at first thinning

	Mean Extraction distance									
Mean dbh	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
10	-798	-803	-809	-814	-820	-826	-831	-837	-842	-848
11	-767	-780	-793	-807	-820	-833	-846	-859	-872	-885
12	-628	-655	-681	-707	-733	-759	-785	-811	-837	-863
13	-535	-571	-606	-642	-677	-712	-748	-783	-819	-854
14	-164	-226	-287	-349	-410	-472	-534	-595	-657	-718
15	140	60	-20	-100	-180	-261	-341	-421	-501	-582
16	460	361	262	163	64	-35	-134	-233	-331	-430
17	936	807	678	550	421	292	164	35	-94	-223
18	1370	1216	1063	909	755	601	447	293	139	-15
19	2170	1976	1782	1588	1394	1200	1006	812	618	424
20	2453	2243	2032	1822	1612	1401	1191	980	770	559

Table 8.5: Predicted profit (€) per hectare using CTL harvesting, sale of pallet and sawlog, seasoning of pulp for 1 summer, chipping using the Jenz 700 roadside chipper, sale of woodchip, in Sitka spruce plantations at first thinning

	Mean Extraction distance									
Mean dbh	100	200	300	400	500	600	700	800	900	1000
10	-806	-812	-818	-823	-829	-835	-841	-847	-852	-858
11	-749	-763	-776	-790	-803	-817	-830	-844	-857	-871
12	-565	-592	-619	-646	-673	-700	-727	-754	-781	-807
13	-442	-479	-516	-552	-589	-625	-662	-699	-735	-772
14	-14	-77	-141	-204	-267	-330	-393	-456	-520	-583
15	327	245	163	81	-1	-83	-165	-247	-329	-411
16	675	574	473	372	271	170	69	-32	-133	-234
17	1194	1063	932	801	670	539	408	276	145	14
18	1658	1501	1345	1188	1032	875	719	562	406	249
19	2479	2282	2086	1889	1692	1496	1299	1102	905	709
20	2791	2578	2364	2151	1938	1724	1511	1298	1084	871

Table 8.6: Predicted profit (€) per hectare using CTL harvesting, sale of pallet and sawlog, seasoning of pulp for 2 summers, chipping using the Jenz 700 roadside chipper, sale of woodchip, in Sitka spruce plantations at first thinning

	Mean Extraction distance									
Mean dbh	100	200	300	400	500	600	700	800	900	1000
10	-877	-883	-889	-896	-902	-908	-915	-921	-927	-934
11	-813	-827	-842	-857	-871	-886	-901	-916	-930	-945
12	-605	-634	-663	-693	-722	-751	-780	-810	-839	-868
13	-470	-510	-549	-589	-628	-668	-707	-747	-786	-826
14	-7	-74	-142	-209	-276	-343	-411	-478	-545	-613
15	353	266	179	92	5	-82	-169	-256	-343	-430
16	715	609	502	396	290	184	77	-29	-135	-241
17	1254	1117	979	842	705	568	430	293	156	18
18	1730	1567	1404	1241	1077	914	751	588	425	261
19	2563	2359	2155	1951	1747	1544	1340	1136	932	728
20	2883	2662	2441	2220	1999	1779	1558	1337	1116	895

Table 8.7: Predicted profit (€) per hectare using Whole tree felling, seasoning of the trees for 1 summer, terrain chipping of the trees, and sale of the woodchip, in Sitka spruce plantations at first thinning

Mean dbh	Mean Extraction distance									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
10	-204	-214	-247	-300	-354	-419	-484	-556	-627	-694
11	-89	-103	-148	-214	-290	-367	-451	-541	-630	-712
12	155	134	65	-33	-141	-256	-373	-505	-631	-756
13	317	291	205	87	-44	-185	-320	-479	-626	-777
14	828	777	639	458	247	45	-165	-396	-619	-842
15	1184	1107	936	703	451	199	-67	-349	-616	-886
16	1587	1477	1257	974	657	363	45	-285	-600	-920
17	2055	1905	1627	1282	905	552	178	-219	-598	-968
18	2513	2315	1982	1589	1147	733	303	-150	-595	-1011
19	3327	3022	2591	2090	1550	1041	524	-21	-573	-1064
20	3579	3231	2781	2253	1678	1137	601	2	-562	-1077

Table 8.8: Predicted profit (€) per hectare using Whole tree felling, seasoning of the trees for 2 summers, terrain chipping of the trees, and sale of the woodchip, in Sitka spruce plantations at first thinning

Mean dbh	Mean Extraction distance									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
10	-234	-244	-277	-331	-385	-449	-514	-587	-658	-725
11	-113	-127	-172	-238	-314	-390	-475	-564	-654	-736
12	145	125	56	-43	-150	-266	-382	-515	-641	-766
13	316	289	203	85	-46	-186	-322	-481	-628	-779
14	851	800	662	482	270	68	-142	-373	-596	-818
15	1225	1147	976	743	491	239	-27	-308	-575	-846
16	1646	1537	1316	1034	717	423	104	-225	-541	-860
17	2136	1987	1709	1363	987	633	260	-138	-517	-887
18	2614	2415	2082	1689	1248	833	404	-49	-495	-910
19	3460	3155	2725	2223	1684	1174	657	112	-440	-931
20	3722	3374	2925	2396	1821	1280	744	146	-419	-934

In tables 8.4 through 8.8 the positive cash flows are presented in green, while conditions where a negative profit was the outcome are presented in red. In the case of the CTL harvesting system with sale of all roundwood products, the lowest levels of mean dbh and mean extraction distance where the system returns a positive profit is 15 cm dbh and 100 m extraction distance. The profit is predicted at €140 per ha. Chipping the pulp wood and selling it as woodchip gives no advantage in the context of a positive profit at lower factor levels, but it does return a higher profit: €327 per ha after one summer drying, and €353 per ha after two summers. If employing whole tree harvesting with terrain chipping at the same factor levels the profit is considerably higher at €1184 per ha after 1 summer drying, and €1224 after two summers. This trend continues up through the dbh factor levels where at 20 cm dbh and 100m extraction distance, the profit returned for the CTL harvesting with sale of all roundwood products is €2453 per ha, and whole tree harvesting with terrain chipping after 2 summers drying returns a profit of €3722 per ha. However, because of the large impact that extraction distance has on the terrain chipping system, at 20 cm dbh, both systems return the same profit at an extraction distance of approximately 550 m.

For easy comparison, table 8.9 displays the system which has returned the highest positive profit for each combination of mean dbh and mean extraction distance. The results show that, in the simulation environment, the research question has been answered:

A whole tree harvesting and terrain chipping system is more favorable than a CTL system, from a profit perspective, as a method for first thinning Sitka spruce plantations in Ireland in conditions where the mean dbh of the stand is between 13 cm and 20 cm, and the mean *extraction distance is 400 m or less. At a mean extraction distance of 600 m or less, the whole tree harvesting and terrain chipping system is also more favorable if the mean dbh of the stand is between 14 cm and 18 cm.*

Table 8.9: Predicted highest positive profit for harvesting systems in Sitka spruce plantations at first thinning

Icons indicate the system which has returned highest positive profit under the conditions

Mean dbh (cm)	Mean Extraction distance (m)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
10										
11										
12	4	4	4							
13	4	4	4	4						
14	5	5	5	5	5	5				
15	5	5	5	5	5	5				
16	5	5	5	5	5	5	5			
17	5	5	5	5	5	5	3	3	3	3
18	5	5	5	5	5	3	3	3	3	3
19	5	5	5	5	3	3	3	3	3	3
20	5	5	5	5	3	3	3	3	3	3

1 = CTL harvesting, sale of all roundwood products

2 = CTL harvesting, sale of sawlog and pallet, seasoning of pulp for 1 summer, chipping of the pulp with the Jenz 700 roadside chipper, sale of chip

3 = CTL harvesting, sale of sawlog and pallet, seasoning of pulp for 2 summers, chipping of the pulp with the Jenz 700 roadside chipper, sale of chip

4 = Whole tree felling, seasoning of whole trees for 1 summer, terrain chipping of the whole trees, sale of chip

5 = Whole tree felling, seasoning of whole trees for 2 summers, terrain chipping of the whole trees, sale of chip

However, it must be noted that the systems comparisons do not take relocation costs into account. The cost of relocating the machines may be disproportionate for each system, which may cause the overall difference in profit margins to change. This may be especially true for small private forests on marginal farm land. For these small parcels of land, the cost of the transportation of the machines to a site will constitute a large proportion of the total cost. In the case of the CTL system with sale of all roundwood products, only two machines need to be transported to the site. Whereas, in the case of whole tree harvesting and terrain chipping, four separate machines (including motor manual) will need to be relocated to each forest. To investigate the impact of these relocations would require an additional study of the distribution of forest sizes, and possibly even their spatial distribution.

8.4 Concluding remarks

Whole tree harvesting and terrain chipping can potentially make thinning Sitka spruce plantations viable at three levels of mean dbh below that of the CTL system. This means that a forester may be able to engage in first thinning when the mean dbh of the stand is 12 cm by adopting whole tree harvesting, while the forester will have to wait until the mean dbh has reached 15 cm for CTL to become cost effective. Silviculturally, this may be beneficial to the overall revenue from the plantation. Quantifying those benefits was outside of the scope of this study, so too were any negative impacts from the systems (e.g. residual stand damage), but it can be postulated that any system which makes management decisions less constrained to immediate financial return should be seriously considered. However, the advantage of using whole tree harvesting and terrain chipping is only applicable to extraction distances shorter than 500 m. The sale of sawlog and pallet products with the chipping of the pulp wood was most profitable at extraction distances greater than 500 m, but only at a mean dbh level of 17 cm or greater.

Chapter 9: Overall conclusion

This dissertation has successfully evaluated parameters affecting a number of supply chains that can be used when harvesting Sitka spruce first thinnings in Ireland. Furthermore, the harvesting methods used in the supply chains were then compared in a simulated environment to asses the conditions in which each system could viably operate (from a profit perspective). This information could be of benefit to forest managers and harvesting contractors who will be engaging with the privately owned forest resource that is rapidly expanding in Ireland. With the increased demand in biomass that is forecasted in Ireland over the coming years, the whole tree harvesting and terrain chipping system can have role in managing this resource. The method has been shown to have a higher positive profit than the CTL method under many conditions, and recovers more volume per hectare than the CTL systems.

9.1 Major findings

The major findings of the dissertation are:

- Kozak's taper equation has the ability to accurately model the taper of trees at first thinning in Ireland when parameterised using field data. A Chapman Richards model can be parameterised to model tree height from the same field data, and together the two models can predict assortment volumes from dbh measurements with a low SEE of 0.0098 m^3.
- The Weibull probability density function was parameterised to model the dbh distribution of thinned Sitka spruce plantations at first thinning in Ireland. By modelling dbh distributions for a range of mean dbh levels (10 cm to 22 cm), and

using the models developed in chapter 2, it was possible to predict volumes for each mean dbh level. The merchantable volume ranged from 10 m^2 ha^{-1} to 168 m^3 ha^{-1}, CTL volumes range from 3 m^3 ha^{-1} to 168 m^3 ha^{-1}, and whole tree volumes range from 20 m^3 ha^{-1} to 220 m^3 ha^{-1}. These results identify how the mean dbh of the stand at first thinning will greatly affect the capacity of the thinning operation to cover costs, and how at lower mean dbh levels, the adoption of whole tree harvest has the potential to recover 560% more volume than the CTL system.

- A quadratic model has been used to describe the relationship between harvester productivity and harvested tree volume, at the tree level. This model predicts that for harvesting cost reduce as mean dbh level increases. At a mean dbh level of 10cm, the predicted cost of production is €285 per m^3, reducing dramatically to €12 per m^3 at a mean dbh level of 20 cm.
- A forwarder model was developed to describe the relationship between forwarding time, extraction distance, load volume, and piece count. The model predicts that the cost of forwarding ranges from €4 and €24 per m^3 depending on the mean dbh level of the stand, and the mean extraction distance.
- A model of a roadside chipper was developed to relate productivity of the chipper to mean piece size. The model predicts the cost of production will range between €3.31 per m^3 and €3.69 per m^3, depending on the mean dbh level of the stand.
- A discrete event model of the Silvatec terrain chipping system was developed to simulate the interaction of the terrain chipper and chips, and to estimate the productivity and cost of the system as a whole. The simulations found that the Silvatec terrain chipping system can be expected to operate at a cost of between €12

per m^3 to €43 per m^3, depending on the extraction distance and mean dbh level of the stand.

- The Silvatec terrain chipping system productivity is greatly affected by extraction distance, so much so that at a distance of 500m or greater the mean dbh level no longer has any effect.
- By evaluating the systems in terms of profit from the sales of the products, it was estimated that at shorter extraction distances (<500 m) the whole tree terrain chipping system was most profitable.
- The sale of sawlog and pallet products with the chipping of the pulp wood was most profitable at longer extraction distances (>500 m), but only at a mean dbh level of 17 cm or greater. This is the effect of the terrain chipping system's vulnerability to long extraction distances.

The Forest Energy Programmes (Kofman & Kent 2007, Kent *et al.* 2011) were the first major studies on wood energy supply chains in Ireland. The empirical data for the projects was collect by the author of this dissertation as a member of the research team. Therefore, this dissertation reflects the state of the art knowledge for the development of wood energy supply chains in Ireland. This dissertation has added value to the existing published reports from the programmes, and thereby added an original contribution to knowledge in the Irish forestry sector. The study also has developed a tool, in the form of a dbh to height and taper model, which has a very significant application in the management of first thinning operations in Ireland.

The empirical data was used to develop models to represent the individual elements in the supply chains. This allowed for the harvesting systems to be compared in a simulated environment. Importantly, models were not only developed for the machine operations, but also for tree volume data at the tree level. These models predicted the dimensions of every individual tree in the simulated environment. This allowed for the volumes attributed to each assortment to be predicted for every tree, including dimensions and number of pieces. The productivity models fed off this data, relating the machine cycle time to tree level data. Although this was an ad-hoc solution to the data problems in this study, the methodology does have merit, and could be applied to forest operations modelling in general. The benefits include: it overcomes the “does less: costs less” problem, allows for the integration of supply chains, values can be attributed to the assortment combinations, and evaluates harvesting systems on an area basis, rather than volume.

9.2 Limitations to the study

Thinning operations are a silvicultural practice, and so any decision to thin must be primarily decided within the limits of good silvicultural practice, or else future revenue streams will be greatly affected. The operational cost based models developed in this study are not capable of identifying all the silvicultural needs or constraints which a forest manager may need to adhere to. Therefore, these models can only be used to support the knowledge and expertise of the Irish forest managers. Also, the study does not take into account the negative site impacts of any of systems trialled. If one system causes significantly more residual stand damage, it could have long term implications that reduce the value of the stand. Further investigations into the site impacts of the systems would be beneficial future research.

Also, this study did not cover the road haulage aspect of the supply chain. Because woodchip production within the forest road network is not common in Ireland, chipping systems may not be able to interact with the road haulage vehicles at all locations. Further investigation on the forest road network and its suitability for maneuvering both chippers and haulage vehicles into position for chipping is required. Discrete event simulation could be employed to model these interactions, and describe the scenarios where operations can proceed.

The study is also only concerned with very few machine systems. There are many alternatives to the machines, thinning methods, and assortments described here. Harwarder machines have the ability to harvest and forward, and may have an important role in the harvesting of small forest areas in the future. Because only one machine is required on the site, the transportation and relocation costs are greatly reduced. Tractor mounted terrain chippers use normal agricultural tractors as the base machine of the chipper, and tractor and trailer units for the forwarder. These systems have a significantly reduced machine rate cost as when the machines are not employed in forestry operations, they can be used for agricultural activities.

9.3 Recommendations

An overview of a proposed methodology for a work study for a CTL harvester follows. An approach similar to this could easily be adopted for other forest operational systems.

- A sample of trees in the forest is felled with a chainsaw, and measured for dbh and total height. The diameter of each tree is measured at 1 m intervals from the base to the tip. A local taper equation and dbh to total height equation is developed for the stand / locality. If this is too time consuming or costly, the most local taper equation and dbh to total height model should be used.
- A sample of the trees to be harvested are measured for dbh, and marked with a system that allows the researcher to identify the dbh when the tree is being harvested. (if possible, all trees would be marked, however this is probably too idealistic). This gives the dbh distribution of the stand (or of the trees being harvested in a marked thinning)
- The dimension specifications of the assortments that the contractor will be cutting are received from the operator.
- An elemental time study of the harvester operating is performed. Each cycle is the operation of harvesting and processing a single tree. The number of each assortment harvested from each tree is recorded. When a sample tree is harvested, the dbh is also recorded on the data logger.

When analysing the data, the sample tree data can be used with the local taper equation and dbh to total height model to predict the individual volumes of the assortments being harvested in each tree. The dbh distribution can then be used to predict for the whole stand. Regression analysis can be used to develop detailed models for the productivity of the harvester. The assortment volumes produced are described in great detail; it is a theoretical volume for each individual log. This could be used to great benefit in discrete event simulations down the supply chain. Models could be developed easily which track individual products through the whole supply chain, from tree to mill, and beyond, identifying where the most cost benefit streams are.

The ongoing National Forest Inventory is making a wealth of data available on the condition of the growing stock in Ireland. Other research such as the geo spatial forecasts (Phillips et al., 2009) , the Coford CLUSTER project, and the Teagasc SUPPLYCHIP project are describing management goals and issues over large areas. At a high resolution, the Treemetrics team are describing individual trees and stands in great detail. There is a knowledge gap in the productivity of the machine systems that are used to carry out the management operations. The productivity and cost of operations will vary depending on site and tree parameters, some of which have been described in this dissertation and others that have not. Machine productivity data should be developed which can feed into other research, such as geospatial forecasts, and GIS management tools. This would allow researchers, both presently and in the future, to describe the operational elements of forest management, such as: costs, time for operation, and number of machines required in a catchment area to facilitate its management.

Many international research institutes have been developing these productivity data in their own countries. The data is then used in simulation studies to look at a wide range of supply chain configurations using actual stand plot data from inventories, e.g. Asikainen (2001) and Väätäinen *et al*. (2006)

The development of this data would require an in-depth study of machine operations in Ireland. This would involve the gathering of information on a wide range of impacting factors. Currently, Ireland has a number of representatives on the European Cost Action programme FP0902, which is dealing with forest harvesting machine productivity, and operations systems modelling. Through the Cost Action programme, a high level of international knowledge is already being transferred on these specific subjects.

Ambitious all encompassing research trials, such as the Forest Energy Programmes, may sacrifice the resolution of the data. The man power required to capture all aspects of the data to a high enough resolution from all elements in real time is enormous, so much so that it could actually impede the operation. The all encompassing trial may only give a case study result, as was seen with the Forest Energy Programmes. This is not to undermine the logistical accomplishment of Forest Energy Programmes. At the programmes core was an investigation to assess *if* such systems could operate, in Irish conditions, by actually trialling the complete supply chain. As the trials were successful, the next step is to describe *how* the supply chains operate. It is tempting for a researcher to look at a supply chain and perceive that it is possible to measure all the elements at once. This is probably because, from the outside, supply chains seem simple. Also, researchers may have little or no experience in forest operations modelling, and so the end goal may be a definitive result of "x", not realising that in forest operational systems there are so many factors affecting "x", that usually x=f(a,b,c,d…), and that, "x" by itself can be meaningless.

It is recommended that future research in this field be modular in its design. That the research be driven to investigate the factors affecting individual elements of the supply chain, leading to overall system simulations that can return a great deal of information from experimentation. One barrier to this is that the dissemination of the results immediately becomes more complex, and the study enters the framework of a "simulation study", a concept that contractors and machinery operators may trust. As the fundamental purpose of this research field is to support industry, there must always be a provision made to inform the “person on the ground” with information that is beneficial to them. Often, (it has been experienced) machine operators only want simple information on the productivity experienced on a site they were working on, regardless of the levels of impacting factors, or the implications of these on other sites, i.e. they prefer the definitive “x” result. From conversations with the contractors, it is obvious that they, unknown to themselves, use this information to perform mental simulations, using their experience to gauge how site factors have affected the results, and how this will transfer to other conditions.

One way to provision for both the research requirements and the applied knowledge for the contractor may be with the use of high definition video recording of the operation. Instead of, or in con-junction with, the data logging of an operation a wearable high definition camera could be used to record the entire time study. The data could then be analysed in great detail back in a laboratory at different resolutions for both contractor and research requirements (paper / report). Although this seems like it is doubling the effort of the time study, the most expensive part of the research is when people are in the field. The video footage could also be archived, so that in the future the video could be re-analysed for a project that has different research requirements. In this manner, the time study data is, in a way, future proofed.

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