A Discrete-event Simulation Approach to Improve Efficiency in Stump Fuel Supply Chains

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Abstract

Current concerns about climate change and fossil fuel dependency have intensified interest in renewable energy and increased demand for sustainable alternatives. Softwood tree stumps could be a very interesting renewable fuel assortment. The stump-root system constitutes about 25% of stem volume. In Sweden, stump fuel extraction is not a well-established practice and large resources are currently left in the forest after final felling. The stump fuel supply chain is both challenging and complex due to distance between resource and end-user, bulkiness of the material, initially high moisture and ash content, and number of sub-processes involved.

Optimisation of logistics issues within the stump fuel supply chain is crucial to ensure low delivery cost. Carefully planned stump fuel systems can reduce the supply costs and help deliver the fuel at a competitive price. In this thesis, various systems for stump transport and comminution were evaluated, particularly regarding resource use efficiency and cutting of unnecessary costs. Various factors associated with different aspects such as harvest site characteristics, fuel quality, biomass losses and machine performance were also evaluated in terms of their impact on fuel cost. A discrete-event simulation approach was applied. Models for all machines and activities included, from forest to end-user, were developed and programmed using the ExtendSim™ simulation language.

The simulation results showed large variations in system performance and system cost. The cost of different transport and comminution alternatives differed by approximately a factor of two, irrespective of transport distance. The most cost-effective option proved to be crushing stumps on the ground and using a self-loading truck for wood fuel transport. Minimising idle machine capacity was identified as a key factor in achieving a cost-effective system. Moreover, well-planned stump storage was shown to reduce the delivery cost significantly. The most influential parameter for fuel cost was machine productivity. Enabling machines to operate efficiently throughout the whole supply chain is crucial for system economics and can be decisive for stump fuel feasibility.

Keywords: Tree stumps, wood fuel, logistics, transport, comminution, supply chain, discrete-event simulation, stump fuel, fuel quality, biomass, modelling

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A good hockey player plays where the puck is. A great hockey player plays where the puck is going to be.

Wayne Gretzky

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Eriksson, A., Eliasson, L. & Jirjis, R. (2014). Simulation-based evaluation of supply chains for stump fuel. *International Journal of Forest Engineering*, DOI:10.1080/14942119.2014.892293.

II Eriksson, A., Eliasson, L., Hansson, P-A. & Jirjis, R. Effects of supply chain strategy on stump fuel cost – A simulation approach (submitted to International Journal of Forestry Research).

Paper I is reproduced with the permission of the publishers.

The contribution of Anders Eriksson to the papers included in this thesis was as follows:

I Planned the study in cooperation with the co-authors. Developed the simulation models used. Ran the simulations, interpreted the data and wrote the manuscript with input from the co-authors.

II Planned the study in cooperation with the co-authors. Developed the simulation models used. Ran the simulations, interpreted the data and wrote the manuscript with input from the co-authors.

Abbreviations

AC	Ash content, dry weight basis
CHP	Combined heat and power
d.b.	Dry weight basis
DES	Discrete-event simulation
DML	Dry matter losses
dw	Dry weight
GVW	Gross vehicle weight
$HHV_{d.b.}$	Higher heating value, dry weight basis
$LHV_{d.b.}$	Lower heating value, dry weight basis
$LHV_{w.b.}$	Lower heating value, wet weight basis
$MC_{w.b.}$	Moisture content, wet weight basis
odt	Oven-dry (metric) tonne
PMH	Productive machine hour
SVC	Solid volume content
w.b.	Wet weight basis
ww	Wet weight, also referred to as green weight

1 Introduction

Widespread global concerns about climate change and fossil fuel dependency have increased the interest in renewable energy, both in Sweden and worldwide. There is also great interest in increasing sustainable domestic energy production. In 2012, Sweden's share of renewable energy exceeded the EU target of 49% by 2020 (Directive 2009/28/EC, published on 23 April 2009) and the 50% target adopted by the Swedish parliament, eight years ahead of time (Anon, 2013b).

Sweden's largest renewable energy source is bioenergy, followed by hydropower. Since Sweden is a heavily forested country, the majority of the bioenergy available is derived from forest (Anon, 2013a; Anon, 2013b). However, forest industry by-products such as black liquor, bark, sawdust and shavings are already being almost fully utilised for bioenergy production in Sweden. The potential for future growth and development in the sector lies in increased extraction of primary forest fuels, *e.g.* logging residues, small trees and tree stumps. These materials were previously left in the forest. In Sweden, the largest volume is present in the tree stump assortment (Routa *et al.*, 2013; Anon, 2008). The stump-root system constitutes 23-25% of stem volume (Hakkila & Kehittamiskeskus, 2004). Although contamination by soil is a problem, stump fuel can be of high quality if properly handled throughout the supply chain (Anerud & Jirjis, 2011).

Softwood stumps are currently harvested on only a limited scale in Sweden, due to low profitability and uncertainties concerning the ecological and environmental consequences. Areas of concern include soil disturbance, carbon balance and biodiversity (Persson, 2012; Walmsley & Godbold, 2010; Melin *et al.*, 2009). Stump harvesting is not accepted by the Swedish Forest Stewardship council (FSC-SE). Net national potential of 20.7 TWh per year has been reported, after the gross potential has been reduced with regard to technical, environmental and economic restrictions (Anon, 2008). In Finland, stump harvesting is accepted, and therefore more common. In both countries, stump extraction is carried out mainly in spruce-dominated final felling stands and it can be based on energy or silvicultural considerations (Routa *et al.*, 2013; Kärhä, 2011; Eriksson & Gustavsson, 2008). Heat and combined heat and power (CHP) plants and forest industry itself, are the main consumers of forest fuels, but other future applications and end-users could include bio-refineries, liquid biofuel producers and thermal treatment plants (Tran *et al.*, 2013; Eriksson *et al.*, 2012; Pu *et al.*, 2008).

The supply chain for stumps includes harvesting, forwarding, roadside storage, road transport to the end-user or a terminal, and comminution (size reduction of material) (Korpinen *et al.*, 2007). Stump harvesting is carried out in the snow-free season using excavators equipped with stump-lifting heads that mechanically lift the stumps (Laitila *et al.*, 2008). For both practical and environmental reasons, some of the stumps are left in the ground. This future dead wood debris can act as a habitat *e.g.* for different species of fungi, mosses and insects (Walmsley & Godbold, 2010). The harvested stumps are collected and stored in small heaps in the regeneration area while waiting to be forwarded to larger piles at a roadside landing (Routa *et al.*, 2013).

The stumps are stored at the landing for some time before being transported away. Prior to final fuel use, the stumps need to be comminuted to hog fuel. This process can be done directly at the forest landing before road transportation, or later at a terminal or end-user (Wolfsmayr & Rauch, 2014; Kärhä, 2011). An advantage with landing comminution is that it produces a denser fuel with better transport properties. Utilisation of different machines out in the forest requires thorough logistical and operational planning. Systems with a high degree of machine dependency often face challenges with poor machine utilisation (Acuna *et al.*, 2012; Aman *et al.*, 2011; Spinelli & Visser, 2009), and high-cost machines such as comminution units are often under-utilised (Han, 2010). In general, two different transport concepts are involved; transport of uncomminuted stumps and transport of comminuted stumps. However, the process can be organised in a number of different ways and can involve different vehicles and machines (Eriksson *et al.*, 2014).

Storage is carried out to improve fuel quality and to match stump fuel production to the demand of the end-users (Laihanen *et al.*, 2013; Anerud & Jirjis, 2011). The largest demand at CHP plants is concentrated to the cold winter season, when stump harvest is not possible (Kärhä, 2011). Stumps can also be stored at larger terminals or at the end-user (Anerud & Jirjis, 2011). The storage time required to sufficiently improve fuel quality to customer requirements is often long.

All machines involved within the supply chain, whether idle or active, influence system performance and ultimately system costs. Moreover, all processes within the supply chain influence both fuel quantity and quality. It is important to manage the fuel properly throughout the supply chain. Delivery of fewer stumps or stumps at a lower fuel quality means less energy delivered. In addition, stump amount and location influence fuel cost. Moreover, machine productivity often varies considerably and together this makes the supply chain difficult to overview. One way to enable a system overview is to build simulation models covering possible supply chains. Experiments in a simulation environment are often preferable to real field studies for both practical and economic reasons.

The discrete-event simulation (DES) approach has been proven to be successful in handling stochastic events in the whole supply chain (Banks *et al.*, 2010). DES is also an effective tool when studying complex logistic processes, since it is able to mimic the dynamic behaviour of systems. It takes into account the stochastic aspect of real systems, which can be difficult to assess with analytical methods (Banks *et al.*, 2010; White & Ingalls, 2009). DES has also been utilised when analysing new concepts in biomass logistics (An & Searcy, 2012). The use of DES as an aid in decision-making has gained popularity due to its flexibility and analysis potential (Jahangirian *et al.*, 2010). In contrast to static modelling, DES can incorporate and account for uncertainties, interactions between system components and interdependencies within the supply chain (Banks *et al.*, 2010).

2 Aim, objectives and structure of the work

2.1 Aim and objectives

The overall aim of this thesis was to evaluate various systems for stump fuel delivery in order to cut unnecessary costs and to make the systems more resource-efficient. The evaluation considered how the stump material should be managed and handled during the supply chain to deliver a fuel with maximum value for minimum input of resources.

Specific objectives were to:

- Model and evaluate the resource use efficiency for various machine configurations in terms of idle machine time and to quantify the process costs for each machine and activity related to stump transport and comminution (Paper I).
- Evaluate the influence of 12 supply chain-related factors on the cost of the delivered fuel. In addition, assess the influence of stump quantity and location on the cost of the fuel (Paper II).

2.2 Structure of the work

The thesis is based on Paper I and II, which focused on different stages of the stump fuel supply chain using two different approaches (Figure 1). Paper I used a dynamic and stochastic approach to study transport and comminution of stumps, with the focus on system cost and resource efficiency. Both existing concepts and new concepts were evaluated and a cost-evaluation of different systems operating at different conditions was performed. Paper II covered the whole stump fuel supply chain and the importance of several factors was evaluated using a deterministic approach. The consequences of biomass losses at different stages within the supply chain were evaluated, the effects of changes in fuel quality parameters (moisture content, ash content and dry matter losses) during storage on the fuel cost were investigated, fuel cost-response to changes in productivity and specifications for the machines involved was determined and harvesting site characteristics and their effects on fuel cost were investigated. Both papers used dynamic discrete-event simulation as the methodology.

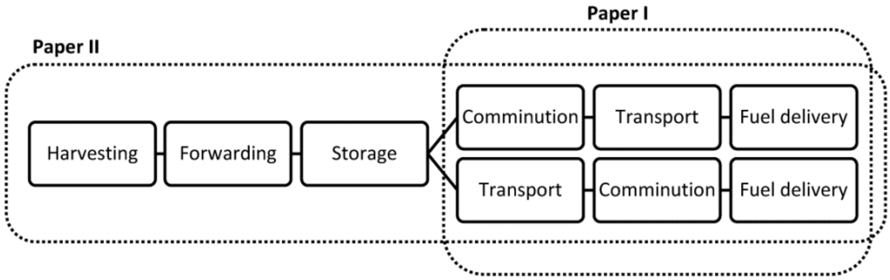

Figure 1. General flowchart showing system boundaries and processes studied in Paper I and II.

3 Background

3.1 Stump as a fuel

The definition of a *stump* is 'the above-ground biomass below the merchantable stem, and its projection underground including the taproot' (Hakkila & Parikka, 2002). The lateral roots are excluded in this definition. The wider concept *stump-root system* includes all roots. However, 'stump' is used a generic name for the whole stump-root system in this thesis.

Globally, stump wood harvesting is not widely practised. It is carried out occasionally to convert forest land to farmland, establishing construction sites and to prevent root rot diseases (Cleary *et al.*, 2013; Vasaitis *et al.*, 2008; Hudson *et al.*, 1994). In Sweden, stumps are often left in the forest after conventional forest operations. Stump extraction *e.g.* to increase the available forest biomass for energy production is possible and could be done without interfering with the timber and pulp wood industries. In the Nordic countries, Norway spruce (*Picea abies* (L.) H. Karst.) stumps are more frequently harvested due to their shallower root system compared with Scots pine (*Pinus sylvestris* L.) stumps (Kalliokoski *et al.*, 2008). Stumps have higher concentrations of energy-rich components, such as lignin and extractives than stem wood (Hakkila, 1975; Eskilsson & Hartler, 1973). In general, the stump is an energy-dense section of the tree, which makes it interesting as a fuel (Nurmi, 1997).

A number of parameters can be used to describe wood fuel quality in general and stump wood quality in particular. The most important parameters are ash content (AC), moisture content (MC) and heating value. Mineral composition and particle size distribution are some of the other important parameters. Woody biomass is composed of cellulose, hemicelluloses, lignin and a small amount of extractives and minerals (Gaur & Reed, 1995).

All wood fuels consist of dry matter and water. Dry matter is what is left after all water is dried away and includes both burnable matter and ash. Ash is a by-product of the combustion process. The AC is expressed as ash weight in relation to total dry weight (dw). Ash composition can affect ash melting behaviour and presence of ash is unwanted, since it can cause sintering, agglomeration and drift problems during combustion (van Loo & Koppejan, 2008). Ash is derived from both (naturally occurring) minerals in the wood and from impurities (both organic and inorganic contaminant) (Thörnqvist, 1985). A natural AC for stump wood of 0.5% has been reported (Hakkila, 1989). Since a large part of the stump grows below ground, soil contamination is unavoidable. Ash derived from impurities varies considerably and is highly affected by procurement and handling methods throughout the supply chain. After final fuel use, ash is generated as a by-product from fuel combustion and contains many nutrients. The mineral outtake through the extracted stumps should ideally be compensated for by returning ash to the forest. For logging residues, such systems for ash recycling are used in Sweden to avoid nutrient depletion.

The basic density (ρ_{basic}), defined as dry weight in relation to green volume, of non-contaminated spruce stump wood is 430 kg dw per solid cubic meter ($m^3{}_s$) (Nylinder, 1979).

About half the weight in fresh woody material consists of water, which is unwanted from a combustion point of view since it greatly affects the heating value (Figure 2). At combustion all water is evaporated, which requires energy (Pottie & Guimier, 1985). Wood is a hygroscopic material and the MC is affected by the handling and storage after harvesting and can both increase and decrease (Richardson *et al.*, 2002; Haygreen & Bowyer, 1996; Hakkila, 1989). The change in MC is driven by many factors, including ambient temperature, relative humidity, wind speed, season, precipitation, tree species and size. MC of wood can be expressed in two different ways; the weight of water in relation to the dry weight (MC, dry weight basis (d.b.)) or in relation to the total sample weight (MC, green or wet weight basis (w.b.)). The latter is used in this thesis. Transportation of fuels containing much water is resource-inefficient, since much of the actual transported goods is water and not burnable matter. Moreover, a moist material causes handling problems during cold weather due to material freezing and storage difficulties relating to the risk of microbial degradation and chemical oxidation (Jirjis & Theander, 1990; Thörnqvist & Jirjis, 1990; Pottie & Guimier, 1985).

Heating value is often divided into two different types; higher heating value (HHV) (also referred to as gross heating value ($q_{v,\ gr}$) or calorific value (CV)) and lower heating value (LHV) (also referred to as net heating value ($q_{p,\ net}$)). HHV is expressed on a d.b.. LHV can be expressed on a d.b. or on a w.b. (Figure 2). The heating value in general refers to the energy liberated during complete combustion per unit mass or volume. The HHV refers to a condition in which all water condenses out from the combustion products. The LHV refers to a situation where this vapour remains, and the latent heat is ignored. Thus plants utilising flue gas condenser technology are less sensitive to wet fuels. The heating value is reflected by the fuel's chemical composition (Gaur & Reed, 1995). A HHV for stump wood ranging from 19.2 to 19.9 MJ/kg dw has been reported (Anerud & Jirjis, 2011) (20.5 MJ/kg dw on an ash-free basis (Anerud, 2012)).

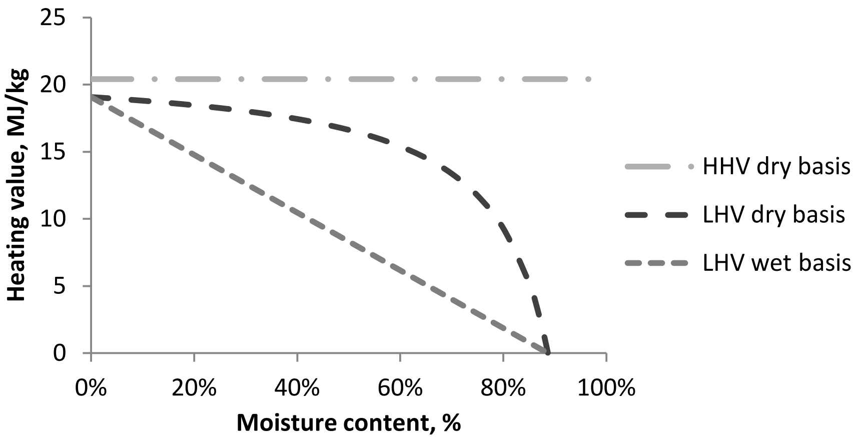

Figure 2. Higher (HHV) and lower heating value (LHV) of stump wood, expressed as a function of moisture content in %.

The particle size and particle size distribution affect the rate at which the fuel is combusted due to fuel geometry affecting available surface reaction area and oxygen movement (Pottie & Guimier, 1985). Biological degradation processes during storage are affected in a similar way. Fuel handling is also influenced by these factors.

3.2 Harvesting

Sweden has a long history of stump harvesting for various purposes including *e.g.* tar production, pyrolysis and land conversion (Lundberg, 1915). The technique currently used for stump harvesting was developed during the 1970s and 1980s in Sweden and Finland to provide pulp wood. This enterprise was later abandoned, but stump harvesting for forest fuel production has since been identified as an interesting area. In Finland, large-scale stump harvesting has therefore been reintroduced during the last decade. An additional value apart from the biomass is improved site preparation.

Stump harvesting is carried out in the snow-free season with unfrozen ground which in the Nordic countries means late spring, summer and early autumn (Kärhä, 2011). A large-scale (around 20 tonnes) tracked excavator equipped with a stump-lifting head uproots and spilt stumps and shakes them to get rid of soil contaminants (Kärhä, 2012; Laitila *et al.*, 2008). There are different stump lifting heads available on the market with slightly different approaches to extraction, but the main function is commonly to mechanical uprooting of a major part of the tree stump (Kärhä, 2012; Anerud & Jirjis, 2011). The Swedish Forest Agency recommends leaving 15-25% of stumps in the ground, based on environmental concerns. The harvested stumps are placed in small heaps in the regeneration area to allow attached soil contaminants to be rinsed off by rain fall (Anerud & Jirjis, 2011).

The productivity of stump lifters depends on local conditions, stump amount and size, equipment and machine operator. Site preparation can be combined with stump lifting, which affects productivity (Kärhä & Mutikainen, 2009). Effort to clean the stumps mechanically through shaking after lifting also affect productivity (von Hofsten *et al.*, 2012a; Laitila *et al.*, 2008). For an average site, productivity values ranging from 2.5 to 6.5 oven-dry tonnes (odt)/productive machine hour (PMH) have been reported (Kärhä, 2012; Lazdiņš *et al.*, 2009; Laitila *et al.*, 2008). For other stands *e.g.* with very small or very large stumps, other productivity values are possible.

3.3 Forwarding

Stump forwarding has many similarities to conventional forwarding of logging residues and aims to move the stumps from the cutting area to a roadside landing that is accessible to trucks. Forwarding of stump parts is possible all year round in favourable conditions. Poorly assembled heaps at the regeneration area, low soil bearing capacity and snow make the operation more complicated and can limit operations in some periods. After operation at one site, the forwarder often has to be moved on a trailer to the next site.

The time taken to forward the stumps is mainly dependent on the distance in terrain, load size and clear-cut area conditions (Laitila *et al.*, 2008). Forwarding season and prevailing weather conditions may also affect the productivity, which in previous studies has been reported to vary between 4 and 11 odt/PMH (Athanassiadis *et al.*, 2011; Lazdiņš *et al.*, 2009; Laitila *et al.*, 2008). Depending on the skill of the driver, condition of the heaps and time spent, different proportions of the harvested biomass are found and collected, meaning that some remains at the cutting area (Nordström *et al.*, 2012; von Hofsten *et al.*, 2012a).

3.4 Storage

Harvested stumps can be stored in heaps on the clear-cut area, in windrows at the road-side, at larger central terminals or at the end-user. Stumps are either stored comminuted or uncomminuted (Anerud & Jirjis, 2011). One reason to store stump parts is that stumps are harvested in summer time and the largest fuel demand is in winter time (Laihanen *et al.*, 2013). Another reason is that the fuel quality of newly harvested stumps does not meet the quality requirements imposed by end-users. Storage is generally performed to improve fuel quality by reducing both AC and MC (Anerud & Jirjis, 2011).

Unacceptably high AC in newly harvested stumps, caused mainly by soil contaminants, is the main obstacle to achieving the desired fuel quality. Storage lowers AC through a weather-driven natural cleaning process. Moreover, attached contaminants tend to fall off during fuel handling. A decrease in AC in newly harvested unstored stumps from 1.4-7% to below 1% after storage has been reported (Anerud & Jirjis, 2011). Laurila and Lauhanen (2010) reported an average AC of 1.7% after storage. Total AC of 3.8-13% is reported in Alakangas (2000) and 1.1-24% in Korpinen *et al.* (2007). However, that is not an upper limit. The storage time required to sufficiently reduce AC is often very long, which is negative from a systems perspective. Long storage times can also be negative for the energy content, as dry matter losses (DML), mainly caused by microbial degradation, can reduce the amount of fuel. DML of 1-10% dw, depending on storage time, have been reported (Anerud & Jirjis, 2011).

The stump usually has a $MC_{w.b.}$ between 40 and 50% directly after harvesting. This decreases rapidly by natural drying during summer storage to around 25% early in autumn. Findings from Anerud and Jirjis (2011) indicate that there is no difference between short-term stump storage in heaps and direct forwarding regarding the effect on fuel quality parameters. A rewetting process starts in the autumn (Anerud & Jirjis, 2011; Laurila & Lauhanen, 2010), but stumps are not as sensitive to re-wetting as logging residues (Laitila *et al.*, 2008). A MC of around 20% after 13-16 months of windrow storage has been reported (Anerud & Jirjis, 2011).

3.5 Comminution

The comminution process results in the transformation of larger biomass units into an acceptable fuel fraction with higher homogeneity. Comminution is generally done for three reasons: a) It increases the surface area, enabling a good combustion process; b) it enables efficient material handling through *e.g.* conveyers: and c) it increases the transport properties of the material due to increased solid volume content (SVC) in each load (Pottie & Guimier, 1985). Comminution can be performed at any location between the source and the consumer (Eriksson & Björheden, 1989). One drawback of comminution is that the storability of the material is drastically reduced. Comminuted material is best consumed soon after the process, since the material faces various threats such as microbial attacks, quality reductions, dry matter losses and the risk of self-ignition (Jirjis, 1995).

Different comminution techniques, *e.g.* chipping, grinding and shredding, are used for forest biomass. The chipper uses sharp tools to cut the material into pieces, whereas the other techniques use blunter tools to smash, tear or crush the material (Pottie & Guimier, 1985). Due to the presence of soil contaminants in stump biomass, it is necessary to use robust machines with blunt tools, *i.e.* grinders and shredders (Goldstein & Diaz, 2005). These machines produce an inferior fuel compared with the chips produced by chippers. The stringy irregular hog fuel has a wide variation in size and shape, with long slivers that can cause feeding problems *e.g.* in conveyers (Hartmann *et al.*, 2006). In this thesis, 'crusher' is sometimes used as a generic name for both grinders and shredders.

Alternative systems with comminution at a road-side landing, a terminal or an end-user exist (Wolfsmayr & Rauch, 2014; Kärhä, 2011). Many of the larger plants in Sweden lack stationary comminution equipment and are dependent on a steady fuel supply of chips. In Finland, stumps are often comminuted with a heavy crusher at a terminal or a heating plant (Laihanen *et al.*, 2013).

Systems based on comminution at the landing increase truck payload, since crushed stumps are less bulky, and thereby reduce the transportation cost. An SVC for uncrushed stumps of around 20%, increasing to around 35% after comminution, can be expected (Ala-Fossi *et al.*, 2007; Pottie & Guimier, 1985; Nylinder, 1979). Comminution at the landing is done by mobile crushers and the stumps can be crushed to a ready fuel or to a coarser fraction just to facilitate transport. In the latter case, further comminution at the end-user is required to produce an acceptable fuel (von Hofsten & Granlund, 2010). Mobile crushers can be truck- or trailer-mounted and are therefore fairly easily moved between job sites. Grinders on a self-propelled track carrier requiring a lowbed trailer for relocation are also available (Bertilsson, 2011). Material crushed at the landing is either deposited on the ground or directly into a truck or bin (container). Moreover, some systems sieve the material already at landing, aiming for higher quality by separating a reject fraction from an accepted fraction (von Hofsten & Brantholm, 2013; von Hofsten & Granlund, 2010). The sieving can be done either by a separate unit in series with the crusher or by an integrated unit within the crusher. Quality improvements are achieved at the expense of some material losses in the reject fraction (Fogdestam *et al.*, 2012; von Hofsten *et al.*, 2012b; von Hofsten & Granlund, 2010).

The performance of crushers varies considerably, depending mainly on comminution technique, engine power, working conditions, operator and ingoing material. Crushing productivity of 5-23 odt/PMH for mobile units has been reported (Nordén, 2009; Asikainen & Pulkkinen, 1998). Pre-shredding produces a hog fuel with larger particles, which is less work-intensive than ordinary grinding. Productivity values for coarse pre-shredding of around 20 odt/PMH can be expected (Fogdestam *et al.*, 2012; Bertilsson, 2011). There may be problems utilising a crusher's fully capacity when operating on narrow landings due to problems with biomass feeding and fuel output through *e.g.* discharge conveyers, especially if the productivity is high (Nordén, 2009). A stationary crusher can operate more efficiently and productivity values of 15-50 odt/PMH can be expected when crushing stump pieces (Anon, 2014).

3.6 Transport

The cost for transportation is significant when utilising forest fuels due to the often high moisture content, low bulk density and non-uniformity of the material (Stokes *et al.*, 1993). The production sites are in general geographically scattered, have a low energy yield per unit area and are distant from the end-user (Möller & Nielsen, 2007; Ranta, 2002). In Sweden, both resource-surplus and resource-deficit regions exist, since both the forest and the population are unevenly distributed (Anon, 2008). This calls for transportation to unite resource and customer. In 2010, average transport distance for primary forest fuels in Sweden was 69 km. Transport distances ranging from 10 up to 90 km were most common, but distances from almost 0 up to 160 km could be seen, and occasionally even longer also occurred (Andersson & Frisk, 2013).

Despite the relatively good energy value in stump wood, stumps are difficult to transport due to their high bulkiness and resistance to compaction. Truck transport of stumps is utilised for relatively short distances. Transportation with truck is flexible, as different production sites that can be problematic for other transportation modes, *e.g.* train or ship can be accessed. In general, biomass transport efficiency, productivity and cost depend on the form in which the biomass is transported, the vehicle used, SVC and $MC_{w.b.}$. Each form may require certain vehicle types and methods for loading and unloading (Pottie & Guimier, 1985). For stump wood, in principle two forms of biomass can be transported; uncomminuted and comminuted.

In Sweden and Finland, forest fuel transportation by truck is restricted to a maximum gross vehicle weight (GVW) of 60 tonnes. The truck payload (maximum allowed cargo weight) is obtained by subtracting the empty truck and trailer weight (tare weight) from the GVW. The permissible truck dimensions often result in a maximum load volume (cargo volume, frame volume) of a truck and trailer combination of 145 m^3 (Ranta & Rinne, 2006). Today, several different truck and trailer concepts are utilised for stump transport. In Finland, the first road transport is often done with stumps in loose form despite their bulkiness. The material is brought to a terminal or directly to the end-user (Kärhä, 2011). Terminals can be seen as a way of increasing quality and delivery security, but at the expense of more handling, transportation and also potentially higher delivery cost (Laitila & Väätäinen, 2012; Kanzian *et al.*, 2009; Gronalt & Rauch, 2007; Eriksson & Björheden, 1989).

As mentioned earlier, only 20% of the load volume is occupied by stumps if they are transported uncrushed (Ala-Fossi *et al.*, 2007). It is the SVC and the basic density of the wood that together determine the fuel bulk density (Pottie & Guimier, 1985). The low load occupancy results in inefficient resource utilisation, with difficulties in achieving maximum payloads and ultimately more expensive transport (Ranta, 2002). The main factors limiting truck load of stumps are particle size, truck load volume, contaminants and moisture content (Ala-Fossi *et al.*, 2007). The truck load is limited either by volume or by weight through the volumetric limitations or the maximum payload. In general, stump loads with low to medium MC are limited by volume, while loads with high MC are often limited by weight. Different combinations of trucks and fuels provide unique breakpoints, but a general pattern is evident (Hall, 2009; Johansson, 2000). Transportation of dry material has benefits such as less machine and road wear, lower diesel consumption and thereby less emissions (Johansson, 2000). Figure 3 illustrates how the fuel bulkiness, expresed as SVC, influence load possibilites on a green and dry basis. A truck with a 140 m^3 load space and a payload of 35 tonnes was considered in the comparision.

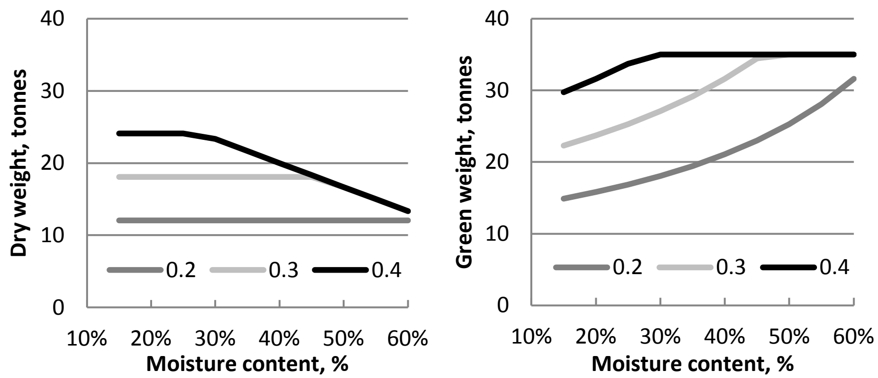

Figure 3. Examples of typical truck payload patterns for different values of the parameter solid volume content (0.2, 0.3, 0.4) as a function of moisture content. A 140 m^3 truck with a payload of 35 tonne was considered.

Four transport vehicle types can be identified as suitable for stump fuel transport; a vehicle dedicated for bulk chip transport, such as a chip truck and trailer or semi-trailer configuration, a chip truck and trailer combination equipped with self-loading possibility, a hook-lift truck and trailer system with interchangeable bins (containers), and a truck and trailer dedicated for loose stump transport.

A chip truck and trailer is a light-weight bulk vehicle designed for maximum payloads and used for comminuted material. A permissible payload weight of around 37-38 tonnes and a truck frame volume of 128-140 m^3 can typically be seen (Liss, 2006; Ranta & Rinne, 2006; Johansson, 2000). The truck can be equipped with its own crane and bucket to enable self-loading, which must otherwise be done by a separate machine or directly after comminution though *e.g.* a discharge conveyor. Mounting a crane decreases cargo space and payload, *e.g.* to 120 m^3 and 30 tonnes, respectively (Liss, 2006). If truck loading is done directly through the crushing unit, loading time is determined by the crusher's productivity, together with the time for the truck to position itself. Irrespective of loading function, unloading is often done by side-tipping both the truck and trailer. Total time at landing for a self-loading chip truck and trailer and total unloading time at industry have been studied by *e.g.* Angus-Hankin *et al.* (1995), Liss (2006) and Ala-Fossi *et al.* (2007). The transport systems with a self-loading truck can be expected to have slightly higher AC due to contaminants from the ground and some losses during loading (Liss, 2006).

A hook-lift truck and trailer is a vehicle that utilises interchangeable bins in which the material is transported. Two or three bins are typically transported (one on the truck and the rest on the trailer), each with a capacity of 35-40 m^3

and the whole combination can have a payload of 32-33 tonnes (Liss, 2006; Johansson, 2000). The truck is equipped with a hook loader for loading the bins onto the truck and the trailer. More than one set of bins is typically used, which enables re-filling at the landing when the truck is elsewhere. Bin handling is time-consuming, since the truck can only handle one bin at a time and therefore needs to first unload its own bin and then relocate bins from the trailer, one at a time, to the truck and then onto the ground. The procedure is reversed when loading bins. At the end-user, the driver must manually open the bin back door and hydraulically tip out the fuel one bin at a time, resulting in the same translocation of bins (Talbot & Suadicani, 2006). Time studies have been carried out on unloading empty bins at the landing, loading new full bins and finally unloading the full bins at an industry (Liss, 2006). The system has also been described in previous literature, including Angus-Hankin *et al.* (1995), Andersson (2000), Alexandersson *et al.* (1984) and Andersson (2011).

A stump truck and trailer is a robust, high-volume vehicle designed for transportation of loose stump parts. It has reinforced cargo space, since stump fuel causes wear due to its irregular shape. A payload weight of 27-30 tonnes and a truck frame volume of up to 145 m^3 can typically be seen (Mortazavi & Johansson, 2013; Liss, 2006; Ranta & Rinne, 2006; Johansson, 2000). The transport truck can work fairly independently and has no strong dependencies on other machines. Process times for loading and unloading have been investigated and reported in the literature (Mortazavi & Johansson, 2013; Lindberg, 2008; Ala-Fossi *et al.*, 2007; Ranta & Rinne, 2006).

3.7 Fuel delivery

Stump fuel is today mainly utilised by larger CHP plants both in Finland and in Sweden (Kärhä, 2011). After entering the gate to the facility, the truck passes over a weightbridge where the total gross vehicle mass is measured. This gives the plant and the seller information about total number of tonnes fuel as received. Moreover, samples for MC determination are often taken in each load and used to approximate amount of energy delivered. If a loose residue truck with crane and grapple is used, it can unload the material directly into a stationary crusher, if available. If the material is transported in comminuted form by a chip truck, it often side-tips the fuel in the receiving area (Figure 4). A hook-lift truck empties the bins backwards, one at a time, in the receiving area (Figure 4).

The stumps do not have to be used exclusively as fuel for CHP plants. The resource as such can have other uses in other sectors, including bio-refineries, gasification plants and biofuel production units (Tran *et al.*, 2013; Eriksson *et al.*, 2012; Pu *et al.*, 2008).

Figure 4. Fuel delivery with two different systems. Left: Truck using side-tipping of both truck and trailer. Right: Hook-lift truck emptying a bin with end-tipping.

4 Methodology

4.1 Discrete-event simulation

System as a concept can be defined as a collection of interacting items forming an integral or complex structure with an intended function (Cassandras & Lafortune, 2008). *Simulation* is defined as experimentation with a model conducted with a specific purpose or the imitation of operation of a real world system over time (Banks, 1998). A *model* can be seen as an abstraction of the real world with a sufficient level of detail for the intended purpose. Both physical and mathematical models can be found. Mathematical models can be solved with *e.g.* analytical solutions and simulation. Simulation can be compared with running field trials, but the real system is replaced with a model. Two different simulation approaches exist; continuous and discrete-event simulation. A model can also be categorised as static or dynamic and stochastic or deterministic. When complex systems are studied, analytical equations describing the system state can be difficult to derive (White & Ingalls, 2009).

Different paradigms and concepts are available in DES, but a general structure exists among the different simulation software products. Discrete-event simulation is dynamic and often stochastic, an approach that is suitable if randomness is expected and system studies over time are desirable. *Inputs* are used to communicate with the system. A collection of *system state variables* holds all the information needed to describe the discrete-event system at a specific point. In DES the system state is only changed when an event occurs. *Output* is a metric used to describe the system results and it is derived from the system state. *Entities* or *items* flow though a collection of blocks that are interlinked and together represent the system. Item movement triggers changes in system state. Each *item* can have attributes and information associated with it. *Activities* are processes within the simulation model. When an item interacts with an activity, an event is created. Activities can be categorised as: delay, queue or logic. *Resources* are similar to items and consist of a finite quantity, *e.g.* machines or workers. A predefined model logic directs the flow of items and an event list handles model execution sequentially. Input data can be set by statistical distributions together with a random number generator that generates pseudo-random numbers defined recursively based on the previous data. Since the inputs are based on randomness, multiple iterations (replications) must be conducted in order to draw conclusions about the system (White & Ingalls, 2009).

Many real-world systems can be seen as discrete-event systems, *e.g.* manufacturing systems, business processes and supply chains. Simulation can provide understanding and act as an aid in finding efficient operating strategies. Frequently mentioned strengths of the DES method are its flexibility, versatility and analysis potential (Ryan & Heavey, 2006) and DES is frequently used as a decision support tool (Banks *et al.*, 2010; Law, 2007). One disadvantage of simulation in general is that it is not an optimisation tool. Development of faster computers, enabling simulation of more sequences of system configurations and variable setups, has facilitated the search for near-optimal solutions with DES (Law & McComas, 2002). Evaluation of multiple scenarios provides the possibility to select the best configuration among the many tested (White & Ingalls, 2009).

Discrete-event simulation is used for tactical, operational and strategic planning in logistics and transportation systems when studying movements of physical goods (Banks, 1998). One frequently mentioned key area suitable for DES is supply chain management (Banks *et al.*, 2002). The dynamics of the system, and not just the average output, can be measured (White & Ingalls, 2009). Discrete-event simulation has been successfully used in many biomass supply chain and logistic studies (Mobini *et al.*, 2013; Karttunen, 2012; Zhang *et al.*, 2012; Mobini, 2011; Asikainen, 2010; Mani *et al.*, 2010; Sokhansanj *et al.*, 2010; Puodziunas & Fjeld, 2008; Ravula *et al.*, 2008; Nilsson, 2007; Iannoni & Morabito, 2006; Nilsson, 2006; Sokhansanj *et al.*, 2006; Väätäinen *et al.*, 2006; Väätäinen *et al.*, 2005; Nilsson & Hansson, 2001; Asikainen, 1998). Moreover, DES has been successfully used when studying new concepts in biomass logistics (Ringdahl *et al.*, 2012).

4.2 Transport and comminution model (Paper I)

4.2.1 Systems studied

In principle, four main systems for transport and comminution (henceforth referred to as S1, S2, S3 and S4) were identified and tested in Paper I. Three of these were based on comminution with a mobile crusher at the landing (S1, S2 and S3) and one on comminution with a larger unit at the end-user (S4). The three systems with comminution at the landing were divided into two different sub-systems based on the comminution method used: *(a) grinding* to an acceptable fuel fraction at the landing; or *(b) coarse pre-shredding* at the landing before transport and final grinding at the heating plant (Figure5).

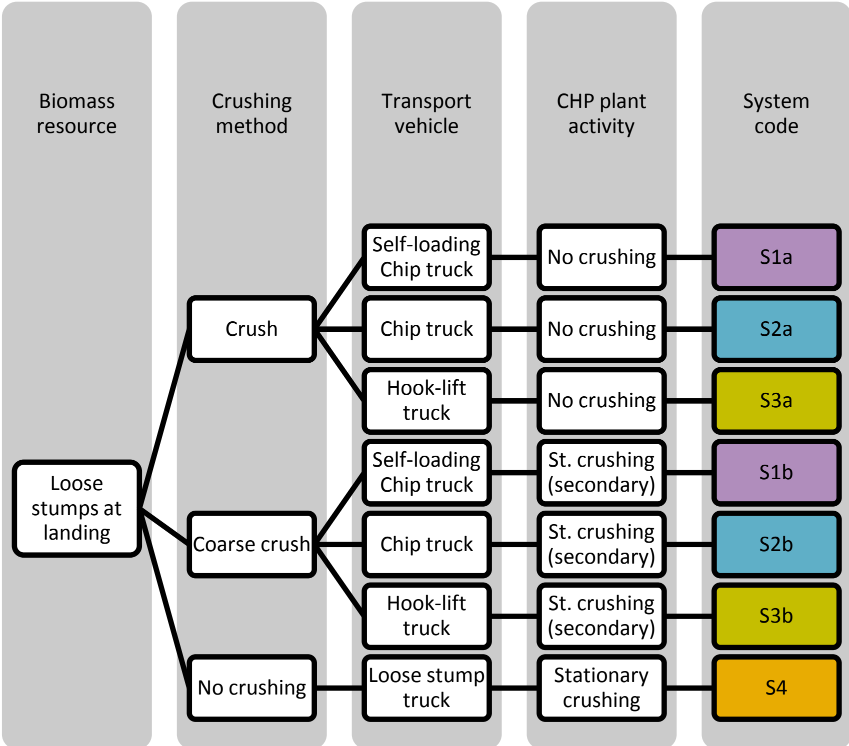

Figure 5. Flowchart showing the system code and the main processes involved in each. St.=Stationary.

(S1) Self-loading chip truck. System S1 included a crusher standing on the road, a truck-mounted loader for loading and moving the crusher, and a self-loading chip truck equipped with crane and bucket for fuel transport (Figure 6). The crusher was moved by the truck-mounted loader between landings and the comminuted material was left on the ground for the chip truck to load and transport to the end-user.

(S2) Chip truck. System S2 included a self-propelled crusher moving beside the road and one up to three chip trucks (Figure 6). The crusher loaded a chip truck on the forest road using a belt conveyor. When the truck left with a full load, the crusher had to wait until an empty truck arrived. When all material

was comminuted, the crusher was transported on a low bed trailer to the next landing and the chip truck followed, if not fully loaded.

(S3) Hook-lift truck. System S3 included a crusher standing on the road, a truck-mounted loader for loading and moving the crusher, a hook-lift truck for serving the crusher with empty bins, and one to three hook-lift trucks with trailer for fuel transport (Figure 6). The crusher was fed by a truck-mounted loader and the material was comminuted into bins being served by one additional hook-lift truck that handled the bin transport between crusher and load/unload area. At the start, three extra set-out bins were transported to the landing with a hook-lift truck and trailer to act as a buffer in the system. In addition, each transport truck had three bins each. When all material was comminuted the crusher was moved by the truck-mounted loader to the next landing and the extra bins were gradually moved to the new site.

(S4) Loose stump truck. System S4 included a self-loading loose-stump truck and trailer. It was used to load and transport stump parts to the end-user. Large-scale crushing equipment was used at the end-user to comminute stumps (Figure 6).

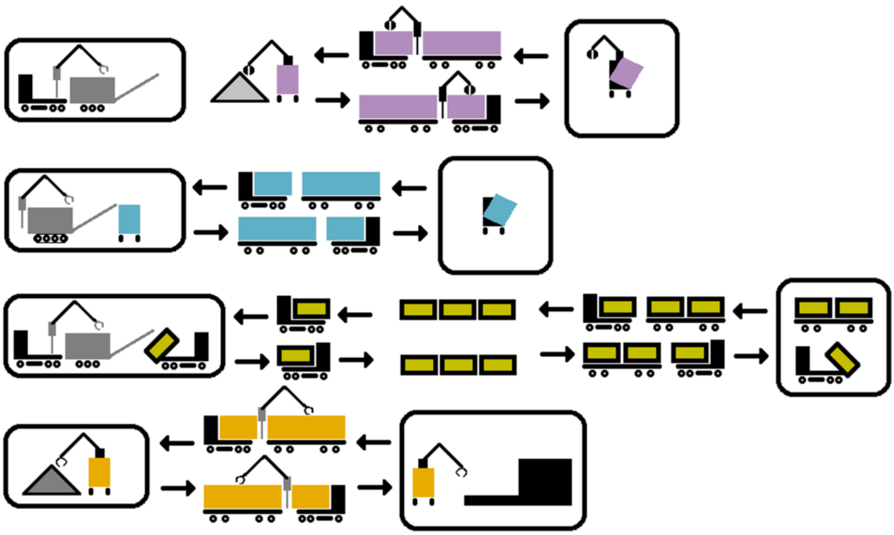

Figure 6. Sketch showing (top to bottom) systems S1-S4 studied in Paper I. Boxes on the left represent comminution and loading at the landing, the intermediate processes is transport and boxes on the right represents unloading and fuel delivery at the CHP plant.

4.2.2 Model description

A dynamic simulation model for biomass process and transportation analysis was developed in a DES environment (ExtendSim) and a representation of the selected study systems (S1, S2, S3 and S4) was programmed. The flows of machines and resources were modelled through a number of interlinked activities. The stumps were transported through the model (from different landings to one customer) by machines circulating within the model. The activities were controlled by data from other model blocks or external inputs, and used both statically and to control probability distributions. Probability distributions created stochasticity in *e.g.* process times and machine break-downs. Communication with the model, both input and output requests, was done with an external spreadsheet.

The objective of the simulated systems was to transport and comminute a given amount of stumps. The simulation was terminated when all initially generated units of stumps were processed and delivered to the end-user. At the start, a set of 20 forest landings with windrow-stored material, each with different geographical locations, fuel property parameters (MC, AC, SVC, ρ_{basic}) and amount, was generated. These objects were initially placed in a queue while waiting to be handled and acted as fictive study sites in which the logistic systems could be examined while handling.

The simulation model for transport and comminution was as follows: The crusher is moved between objects and transforms uncomminuted stumps to hog fuel. After crushing at one location, it continues to the next. In systems S2 and S3, a truck or a bin with available load capacity needs to be present in order to crush, whereas in system S1 the crusher operates independently of the truck.

The objective of transport trucks is to move the material from the landings to one single end-user. In general, the work procedure was as follows: (i) go out to the first object in the queue, (ii) if there are other trucks there, then wait, (iii) load as much as possible given the specifications of the truck and the characteristics of the fuel, if fully loaded go back to the end-user or otherwise go to the next object in the queue and continue to fill up the load capacity, and then (iv) go back to the end-user, (v) unload material and then start over with step (i).

The actual capacity of each truck load is calculated based on the parameters associated with each fuel entity and the specification for the truck (cargo space and allowed payload). An empirical equation is used to calculate average truck driving speed (Ranta & Rinne, 2006).

Machine time can be divided into active time, idle time, service time and downtime. Machine utilisation is defined in the model as the ratio between productive and scheduled machine time. The dynamic model keeps track of the time for each entity in each activity in the system, irrespective of whether it is *e.g.* queue time, waiting time or operating time. All time that is not productive is batched together to an idle component. The model registers the total amount of delivered fuel, time consumption for each activity in the system, cycle time, machine utilisation rate and total accumulated cost of each activity.

4.2.3 Experimental design

All proposed systems were tested on the same sets of objects (study sites) within each simulation run. All seven systems/sub-systems (S1a-3a, S1b-3b, S4) were evaluated. Configurations with one, two and three trucks were simulated for the systems with a high degree of machine dependency, henceforth referred to as hot systems (S2a, S3a, S2b and S3b). The initial quantity of windrow stored stumps at each landing was drawn from a uniform probability distribution, with a minimum of 50 and a maximum of 250 odt. The one way transport distance was handled as an experimental factor, with six discrete levels (25, 50, 75, 100, 125 and 150 km).

Stochastic simulation requires multiple simulation runs (replications) and different methods are available in the literature for choosing the appropriate number (Banks *et al.*, 2010; Law, 2007; Robinson, 2004; Law & McComas, 1991). In Paper I, by graphically studying convergence of the cumulative output, five simulation runs were found to be sufficient, since a large number of internal replications was made when studying long runs. Each simulation run included handling of multiple objects during a long period. Variance reduction through common random numbers was partly used, which also reduced the number of runs required.

4.3 Extended supply chain model (Paper II)

4.3.1 Systems studied

The whole supply chain for stump fuel was considered in the extended model. Two conceptually different systems with comminution at the forest landing or at the end-user were chosen for the analyses. The processes before transport and comminution were common for the two. The alternative with landing comminution (system SI) was chosen to utilise a self-loading truck for fuel transport and the alternative with comminution at the end-user (system SII) were chosen to utilise a truck dedicated for loose stump transport. Both systems were proven to be resource-efficient for all cases studied in Paper I and were therefore selected for study in Paper II. The two systems are similar in structure and therefore easy to compare.

4.3.2 Model description

The supply chain model in Paper II extended the DES model for transport and comminution described in Paper I. Further refinements were made and new sub-modules incorporated in order to model the whole supply chain and to better match the objectives for Paper II.

The model was programmed to enable variation (both static and stochastic) of 12 pre-defined study factors related to handling, fuel quality and machine efficiency. In addition, possible variation in transportation distance (km) and harvesting site size (odt stumps in ground/site) was incorporated in the same way. The cost impact of changes in those factors was examined.

At the start, 10 sites suitable for stump harvesting were generated based on pre-defined conditions and those sites were placed in a queue waiting to be handled. Initial settings for *e.g.* transport distance, available biomass resource, activity times, fuel quality and effectiveness were set prior to simulation and read from a Microsoft Excel input spreadsheet. These settings were stored in attributes associated with each fuel entity (1 odt of stumps) or each harvesting site entity.

In model execution, the harvesting sites are handled one at a time and all machines (excavator, forwarder, crusher and transport truck) are directed to all sites. In brief, one simulation run includes: *harvesting, forwarding, storage* and *transport-comminution* or *comminution-transport.* These activities are followed by *fuel delivery* at one end-user. Transport and comminution are explained in detail in section 4.2.2.

A designated share of all stumps is harvested and later forwarded, meaning that some material is lost. To represent effects on fuel quality during storage, new values for the attributes MC and AC are set and some dry mass is deducted to account for DML. A new value for the parameter SVC is set after comminution, enabling more efficient transport. If sieving at the landing is considered, a share of the dry mass is deducted as reject and new values for MC and AC are set. Moreover, a deduction of some material is made due to loading from the ground.

The simulation model calculates the amount of energy delivered based on the sum of energy quantities associated with each odt fuel (lower heating value, dry basis ($LHV_{d.b.}$)) using an equation derived from Thörnqvist (1984) and van Loo and Koppejan (2008). Both the number of odt delivered and the fuel quality parameters (MC and AC) determine the final amount of energy delivered in MWh.

When all stumps have been delivered to the end-user, the number of odt and the total amount of energy delivered is written to an output spreadsheet, together with the cost of each process in the supply chain.

4.3.3 Experimental design

Simulation experiments were conducted to examine system responses to changes in the 12 study factors (SF) (Table 1). An experimental strategy with variation of one factor at a time was used. A starting base configuration was defined and factor variations within a defined range were studied. This technique enables studies of potential non-linear effects, but is insufficient to detect interactions between variables (Montgomery, 2006).

Table 1. *Base level for each of the 12 study factors (SF) tested in Paper II.*

Study factors		Units	Base level
SF1	Stumps left in ground	%	20
SF2	Stumps left by forwarder	%	5
SF3	Stumps left at landing	%	2.5
SF4	MC after storage	%	30
SF5	AC after storage	%	3
SF6	DML during storage	%	5
SF7	Harvest productivity	odt/PMH*	4.5
SF8	Forwarding productivity	odt/PMH	8
SF9	Crushing productivity	odt/PMH	10/40**
SF10	Load time	min	55/45
SF11	Unload time	min	20/60
SF12	Load size	m^3	120/145

* PMH – Productive machine hour

** When two values are given, the first is for system SI and the second for system SII

These levels were chosen to reflect common variations based on current knowledge. Systems SI and SII were evaluated when operating in a geographical area with 10 sites, each located 60 km from the end-user and with 300 odt stumps in the ground.

The effects of introducing sieving in system SI in combination with landing comminution for heavily contaminated material were also examined. A 25% dry mass rejection, a slightly lower DML and MC, and slightly higher harvest productivity compared with the base case were simulated.

A separate parameter analysis for transport distance and harvesting site size was conducted to study the importance of stump harvesting site selection. During these scenarios, all SF where set to their base level.

4.4 Simulation input data

Calculated hourly machine costs based on a costing template developed and approximations made by the Swedish Forestry Research Institute were used in the models (von Hofsten *et al.*, 2012a; von Hofsten, 2006). The calculations were net cost calculations from the contractor's point of view and exclude *e.g.* profit and forest owner compensation.

Data for machine performance were based on time and performance studies and estimates by operators familiar with the system and studies of similar systems. When data are available, probability distributions can be fitted to the data, but since these systems are new and sometimes unstudied, other information must sometimes be used in input modelling. Examples of information could include physical and conventional limits, the nature of the process as such, or expert opinion. Expert opinion is generally valuable and widely used, since it can often give extreme values and sometimes also the most likely value of a process (Biller, 2010). A more thorough description of input data used can be found in Papers I and II.

4.5 Verification and validation

Validation of a model deals with questions such as whether the right model is being built, whereas verification of a model deals with questions such as whether the model is being built right. The models of the systems in Papers I and II were validated and verified during both the conceptual and the model phase, using a subjective method called structured walk-through. This allowed the model to be checked in a structured way by people knowledgeable about these systems for face validity, by trying to uncover errors and detect faults. Debugging and evaluation of model logic and internal structure were performed. White-box testing aiming to evaluate model logic and internal structure was also performed. Visualisation was used as a tool during execution to monitor system behaviour and comprehensive test runs were conducted. The model logic was also validated and verified by persons familiar with the systems modelled. Both simulation models were found to be reasonable based on these tests. For more information about these methods, see *e.g.* Balci (1994).

5 Results and discussion

5.1 Simulation of stump transport and comminution (Paper I)

Systems S1-S4, including all sub-systems (crushing method) and configurations (number of trucks), were evaluated when transporting and comminuting stumps from different locations to one single end-user. The evaluation was made with cost and a number of other system performance metrics as a base. The results from the simulation experiments carried out are presented in this section.

5.1.1 The crusher

Crusher utilisation rate in the self-loading systems (S1a and S1b) was constant with respect to distance and only limited by the moving time and the machine failure rate. A higher crusher utilisation rate was observed in the grinding system (S1a) compared with the pre-shredding system (S1b) (Figure 7), which was expected and was caused by the lower productivity in the former system. When the productivity is lower, the time spent on crushing is relatively larger in relation to other activities.

When only one chip truck was employed in system S2, a maximum crusher utilisation rate of 43% and 31% was achieved in the grinder and pre-shedding alternative, respectively. Adding a second chip truck almost doubled crusher utilisation (82-98% increase), irrespective of scenario, according to the simulations. A third truck provided significantly higher utilisation except considering grinding at a distance of 25 km, where two trucks were sufficient to keep the crusher occupied (Figure 7).

Significantly higher utilisation rates compared with system S2 were obtained for the one and two hook-lift truck and grinding alternative, especially regarding short transport distances. In those cases, the extra buffering capacity that the set-out bins provided was the factor behind the improvements.

However, with increasing distance this difference decreased. For longer distances, the hook-lift truck system had utilisation rates of the same level as the chip truck system, considering the same cases. Regarding grinding, two hook-lift trucks with three extra set out-bins were sufficient to maintain high utilisation rates for distances up to 50 km. Three trucks were able to occupy the crusher almost fully up to a distance of 150 km (Figure 7). The increased productivity in the pre-shredding scenario in general lowered the utilisation rates achieved compared with grinding.

Both experiences from contractors and studies described in the literature points out the difficulties in maintaining a high utilization rate in these systems, or similar systems (Aman *et al.*, 2011; Spinelli & Visser, 2009).

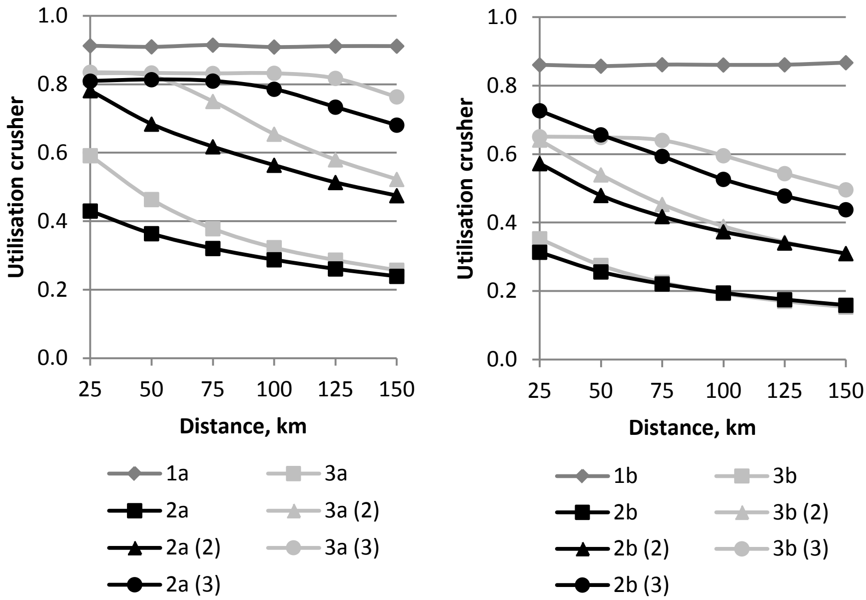

Figure 7. Crusher utilisation for the systems based on mobile comminution at the forest landing (S1-S3) as a function of transport distance. Left: crushing to a ready fuel fraction. Right: pre-crushing before transport. For explanation of system codes, see Figure 5. The number in brackets for each system is number of trucks, if more than one.

5.1.2 The transport unit

The objective of the transport truck is to move the biomass from the forest landings to the end-user. The total turn (cycle) time consists of load, unload, transport and truck idle time. In the one-truck options, no queue time was present and idle time consisted of only time for scheduled breaks. For a distance of 25 km, more than half of the time consisted of loading and unloading, irrespective of system (Figures 8-10). Regarding only the transport unit, identical results were obtained for systems S1a and S1b (Figure 8) since the difference between these lay in choice of crushing method. The same input data were used, even though the shape and size of the material might have influenced loading and unloading times.

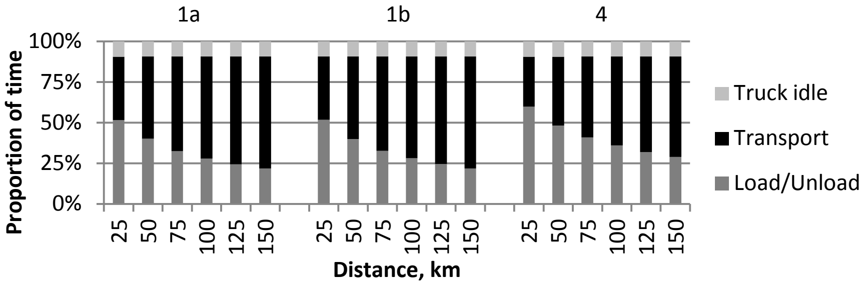

Figure 8. Proportion of time spent on different activities for each transport truck in systems S1a, S1b and S4. For explanation of system codes, see Figure 5.

Considering the systems utilising more than one chip truck, queue time was introduced as a new system component and occurred when one truck arrived at the landing while the previous truck was still there (Figure 9). Truck time spent standing still during loading of crushed material was defined as load time and not considered queue time, since it is unavoidable. With increased number of trucks and decreased transport distance, a larger proportion of truck idle time occurred.

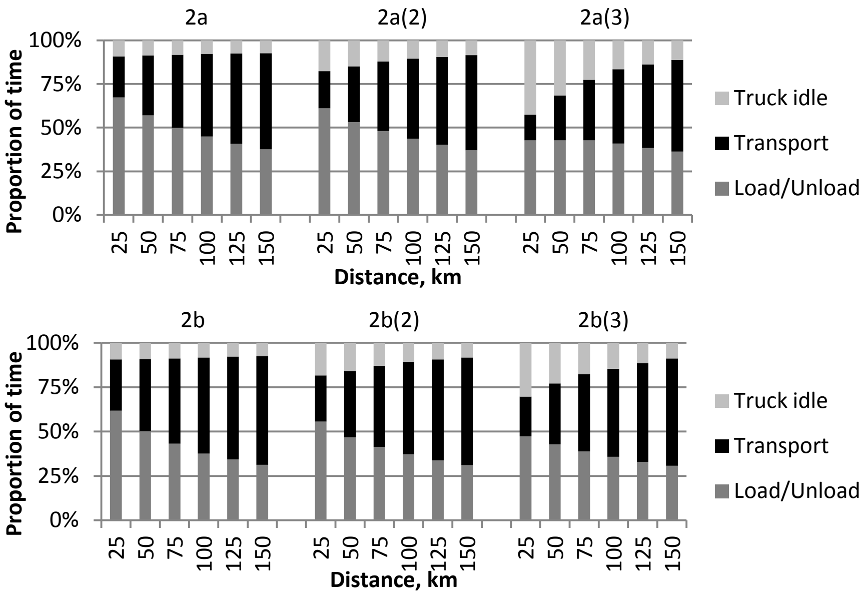

Figure 9. Proportion of time spent on different activities for each transport truck in systems S2a and S2b with 1, 2 and 3 trucks. For explanation of system codes, see Figure 5.

The idle time in the hook-lift truck systems (S3) was defined as for system S2, but with the difference that time waiting for fully loaded bins was also considered queue time. No significant difference was seen between the two crushing methods when one truck was used (Figure 10). This means that three fully loaded bins were almost always ready at the landing when the truck arrived, even for short distances. When more trucks were introduced into the system, waiting time could occur. At worst, nearly 50% of the truck work was idle time.

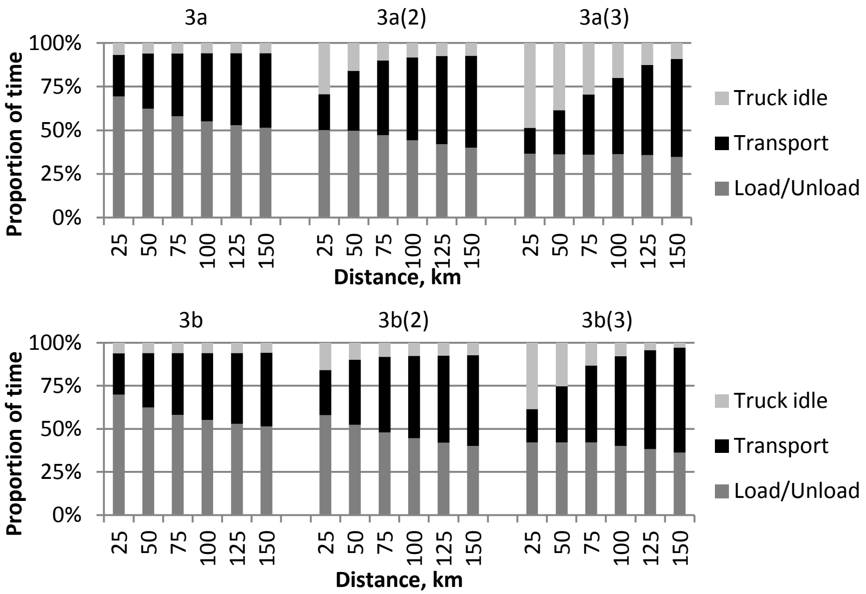

Figure 10. Proportion of time spent on different activities for each transport truck in systems S3a and S3b with 1, 2, and 3 trucks. For explanation of system codes, see Figure 5.

5.1.3 Total system results for transport and comminution

The total system cost, based on the individual cost of each activity, is presented in Figures 11-13. In system S1, the cost difference between grinding and pre-shredding before transport was comparatively small. The general pattern was the same, with the exception that the mobile crushing cost less in the latter case but costs for crushing at the end-user were added on. Systems S1a, S1b and S4 all had an almost linear increase in system costs with increased transport distance (Figure 11). System costs for all three systems were within the same range for short distances, but with increasing distance system S4 became relatively more expensive. This was caused by the lower payload of the stump trucks as a result of fuel bulkiness.

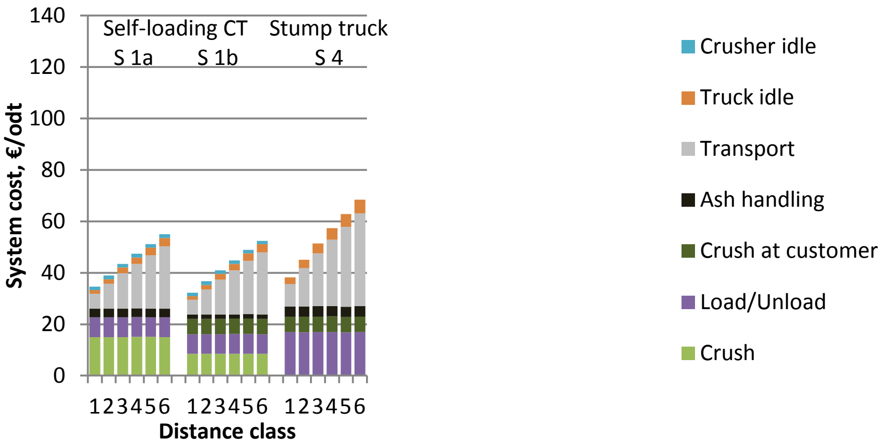

Figure 11. Total system cost for systems S1a, S1b and S4 and cost of each activity for distance classes 1-6, which correspond to transport distances of 25-150 km. For explanation of system codes, see Figure 5.

The general behaviour of system S2 was similar for both sub-systems S2a and S2b (Figure 12). It was found to be preferable to have the truck waiting for some time instead of the crusher, since crusher time was more expensive. Systems which included pre-shredding had a smaller proportion of truck idle time compared with the grinding systems, due to higher expected crusher productivities. The one-truck options had overall high costs because of excess crusher capacity. At the longest distance studied, around half of the total system cost was related to idle crusher time. Considerably higher costs for excess truck capacity were only found in three-truck options operating on short transport distances, and only in the grinding system. None of the configurations (number of trucks used) had a perfect balance between spare capacity of both truck and crusher for any distances studied. Coarsely pre-shredding the stumps before transporting them with three chip trucks always seemed to be a fairly good alternative, based on the simulation results obtained. For the chip truck system, cost figures in the same order as obtained here (Figure 12) and with a similar method have been presented in the literature (Asikainen, 2010).

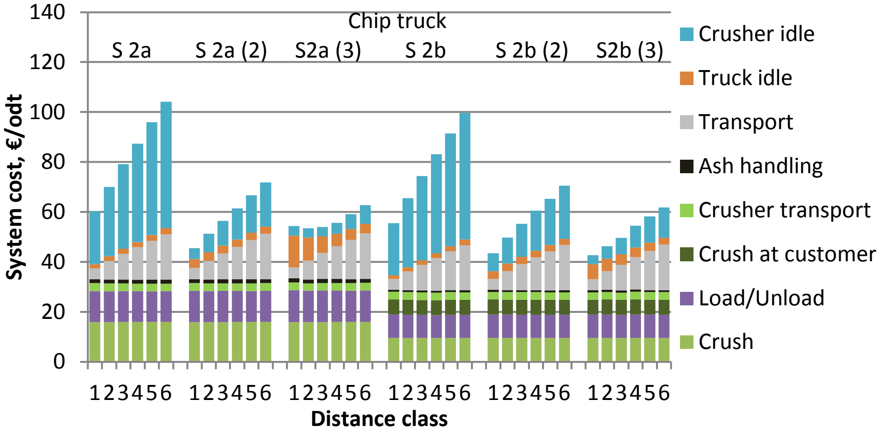

Figure 12. Total system cost for systems S2a and S2b with 1, 2 and 3 trucks and cost for each activity for distance classes 1-6, which correspond to transport distances of 25-150 km. For explanation of system codes, see Figure 5.

The general trend in the hook-lift truck systems was similar to that in the chip truck systems (Figure 13). When there was available truck idle capacity, the costs of idle crusher capacity was hampered. When no truck idle capacity was available, the costs of an idle crusher started to increase with distance. The results showed that the cost for loading and unloading also increased with increasing distance, at least when the crusher had a large proportion of idle time. The explanation is that the extra hook-lift truck that serves the crusher with bins was unutilised during long times. The sub-system with coarse pre-shredding and three transport units was well balanced for all transport distance classes studied and therefore system costs were, in comparison, comparatively low.

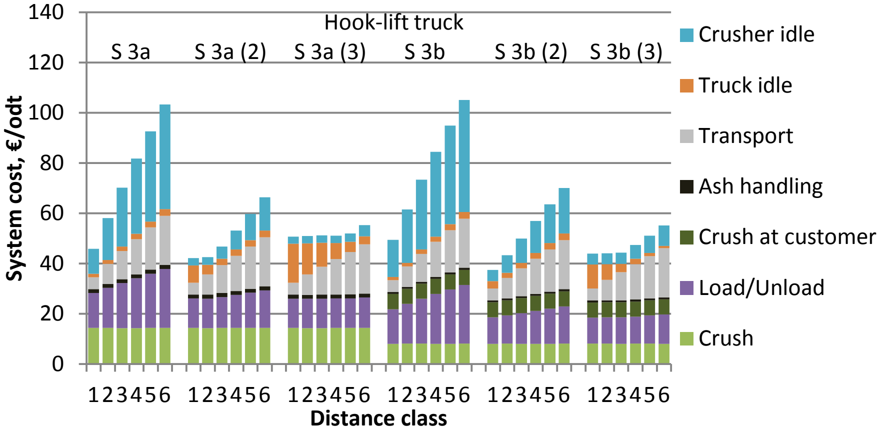

Figure 13. Total system cost for systems S3a and S3b with 1, 2 and 3 trucks and cost for each activity for distance classes 1-6, which correspond to transport distances of 25-150 km. For explanation of system codes, see Figure 5.

In a cost comparison between the three cold systems (S1a, S1b and S4), the difference was comparatively small for short distances. Costs of 34.6, 32.3 and 38.3 €/odt were found when a transport distance of 25 km was studied. At the longest distance studied (150 km), transportation of uncomminuted stumps cost 16.1 € more per odt compared with the least costly alternative (S1b) (Figure 14).

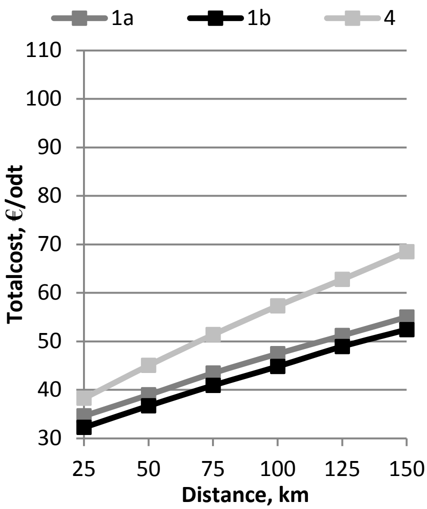

Figure 14. Total cost for transport and comminution as a function of transport distance for systems: S1a (self-loading chip truck and grinding), S1b (self-loading chip truck and coarse shredding) and S4 (loose residue transportation and large-scale comminution).

In a comparison between the two hot systems, S2 and S3, larger variations were found than for the cold systems, S1 and S4 (Figure 15). When the one-truck options were excluded from the comparison, there was less variation. Based on the simulation results, cost transition points between different configurations could be identified. The chip truck system S2 had the transition point between two and three trucks at around 60 and 25 km for sub-systems (a) and (b) respectively. For the hook-lift truck system (S3), the corresponding transition point was at 90 and 50 km for sub-system (a) and (b), respectively.

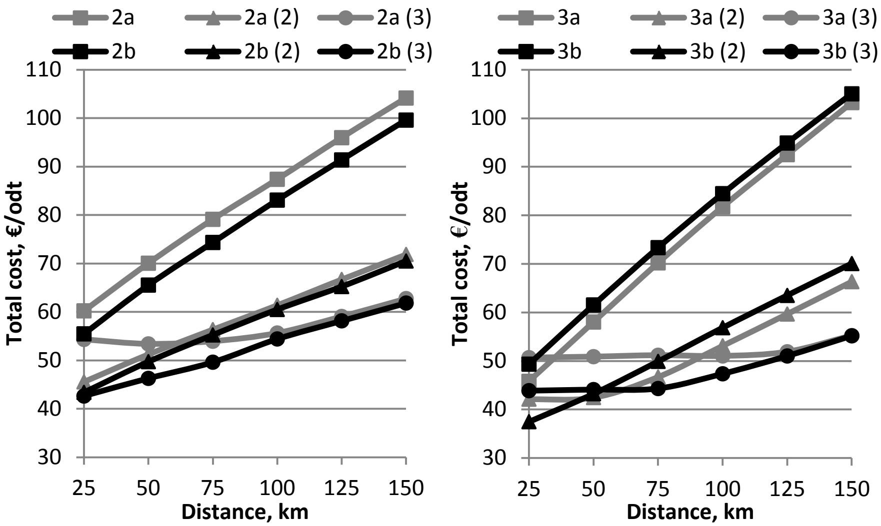

Figure 15. Total cost for transport and comminution as a function of transport distance for systems: S2a (chip truck and grinding), S2b (chip truck and coarse shredding), S3a (hook-lift truck and grinding) and S3b (hook-lift truck and coarse pre-shredding). The number in brackets is number of trucks, if more than one.

The cost varied considerably in an overall comparison between all systems and configurations. For the shortest distances, the cost ranged from 32 (S1b) to 60 €/odt (S2a), while for the longest distances it ranged from 52 (S1b) to 105 €/odt (S3b).

The self-loading systems had the lowest costs for all distances in an overall comparison. Supporting the results, Hall *et al.* (2001) stated that the simplest delivery system often is the cheapest. However, the hook-lift truck system reduced the difference with increased distance.

Besides results based on cost and machine utilisation, these systems can be evaluated based on other output metrics. For example, total time when delivering the initially generated amount of stumps differs for the systems, and can be an important factor in some situation. The loose residue system (S4) made the fuel delivery in 33 days (25 km) and 69 days (150 km). The three hook-lift truck system (S3a(3)) managed to deliver the same amount of fuel within 13 days (25 km) and 14 days (150 km). The latter result is explained by crusher productivity being limiting and transport capacity sufficient (Figure 7) in both cases (25 and 150 km).

5.2 Simulation of the whole stump fuel supply chain (Paper II)

The whole supply chain from stumps in the ground to fuel delivered to a single end-user was modelled in Paper II. A summary of the results from the simulation experiments is presented in this section. The presented change in fuel cost can be related to the fuel cost for system SI and SII being 16.6 and 17.1 €/MWh, respectively, in the base case.

5.2.1 Fuel losses

Every time material is handled, time and resources are invested in the process and extra costs adds on (Hall *et al.*, 2001). The fuel cost is obtained by comparing input (cost of processes) with output (value of delivered fuel). Losses that occur after a process will affect all upstream processes. All losses will affect the amount of fuel delivered, but losses at a later stage in the supply chain will affect more processes than losses at an earlier stage and therefore contribute to more expensive fuel. Not harvesting stumps at the start has minor negative effects on the fuel cost, since no machine time is invested in those units of stumps. A total cost increase of around 3.5-4% could be expected if 40% of the stumps are left in the ground at start compared with all being harvested (Figure 16). The small negative effect is related to a relatively higher cost for machine movements. Neglecting 10% of the harvested stumps when forwarding resulted in around 4.5% increased costs on a system level (Figure 16). Loading material from the ground at landing can result in fuel losses. These losses were found to have a comparatively large impact on the fuel cost, as lost material had been harvested, forwarded to the roadside, stored for some time and, in system SI possibly comminuted. This meant that much unnecessary work had been done by the contractors responsible for upstream processes. In general, system SI suffered more from losses of material at the landing than system SII, since comminution was done before the losses. Material losses of 6% at the landing generated a cost increase of 5.6% and 3.5% for system SI and SII respectively (Figure 16).

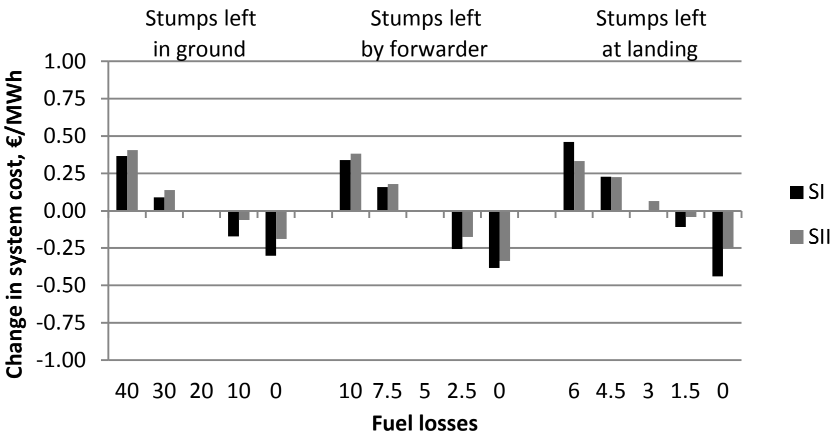

Figure 16. Change in total supply chain cost due to different percentage of stumps being left at various locations in systems SI and SII. For a detailed description of these systems, se section 4.2.1.

5.2.2 Storage outcome

The storage effects on fuel quality are difficult to predict and the AC, MC and DML are influenced by the initial conditions, storage time, prevailing weather and storage composition. General guidelines on how to store stumps are available, but the outcome of storage varies. AC and MC usually improve the fuel with time and DML, on the contrary, deteriorate the fuel with time.

Close to linear effects were found in the parameter analysis for a change in the two fuel quality-related parameters AC and DML, but for a change in MC a non-linear effect was observed. Compared with the reference scenario with 3% AC, a cost increase of 6.8% or 1.15 €/MWh in both systems was found when an AC of 9% instead was considered. A 1% change in AC resulted in a cost increase or decrease of 1.1% or €0.19 for every MWh. A cost increase of 2.6%, or 0.4 €/MWh, was found when 9% DML was considered compared with the base case of 5%. Every 1% of loss in dry matter resulted in an average cost increase of 0.6% or €0.10 for every MWh.

A large increase in fuel cost occurred when a fuel with MC >35% was transported in system SI whereas system SII was more tolerant to increased MC in the fuel. This is because uncomminuted stumps are bulky and the loads are limited by volume rather than weight in the SII system. The cost difference between handling a fuel with low MC (15-35%) and wetter fuel (MC 45-55%), was large, especially for system SI (Figure 17). Avoiding excessively wet fuels is crucial for system viability. A MC after storage of 35% compared with 55% reduced the fuel cost by 17% and 10%, for system SI and SII, respectively.

This highlights the importance of proper storage. Ranta (2002) stated that storage cost might be significant and often underestimated.

The input values tested in Paper II reflected what could be observed in common practice. Thus the cost reductions listed can be achieved passively and costless during storage, as opposed to *e.g.* investment in a more productive machine unit.

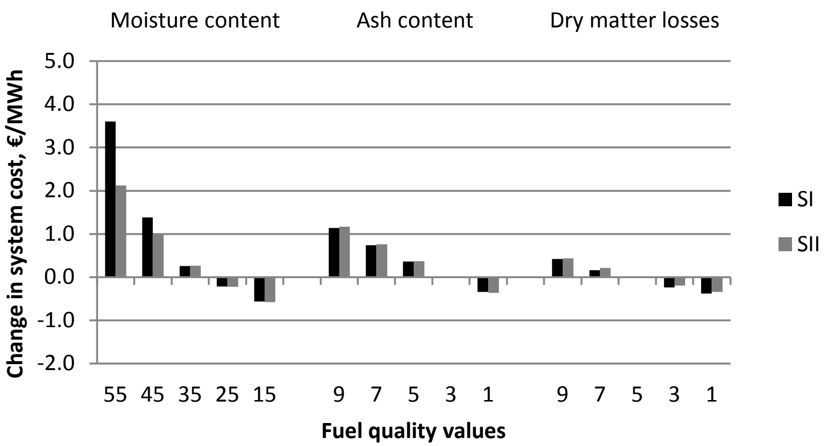

Figure 17. Change in total supply chain cost due to different storage outcomes regarding moisture content, wet basis (%), ash content, dry basis (%) and dry matter losses (%) in systems SI and SII. For a detailed description of these systems, see section 4.2.1.

5.2.3 Machine productivity

Machine productivity can vary considerably. Identical study conditions are unattainable in actual operations and beforehand predictions based on assumed conditions are difficult to achieve. All changes in machine performance tested here caused significant changes in the system outcome.

The most influential changes between the two extreme input values tested were in harvest productivity, closely followed by forward productivity (Figure 18). Suitable harvest area selection and machine choice can help to hold these parameters at high levels.

When the harvest productivity was increased by 22%, from 4.5 to 5.5 odt/PMH in system SI and SII, the fuel cost decreased by 5.5 to 5.3%, or 0.92 to 0.91 €/MWh, respectively. A decrease in productivity of the same magnitude resulted in cost increases of 8.7 and 8.4%, respectively. Additional decreases in productivity resulted in even further increases in cost (Figure 18). A 25% higher forward productivity compared with the base case resulted in a cost decrease of 3.6 and 3.7% for systems SI and SII, respectively. A 25% decrease in productivity instead resulted in a 6.2 and 5.9% cost increase for system SI and SII, respectively. For a change in crushing productivity, different values were examined for the two systems.

Resources must be spent in keeping these three parameters at high levels, since this will significantly lower the total delivery cost. Avoiding the lowest productivity values tested here is crucial for system economics.

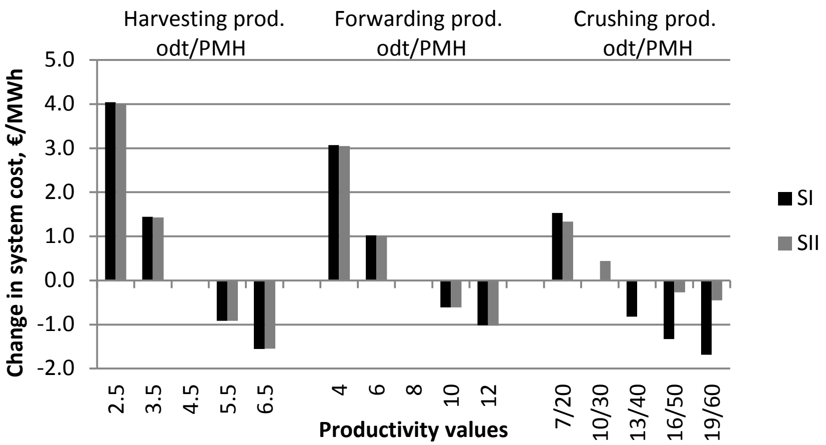

Figure 18. Change in total supply chain cost caused by different machine productivity values in systems SI and SII. When two values are given, the first is for system SI and the second for system SII. For a detailed description of these systems, see section 4.2.1.

5.2.4 Transport truck parameters

The truck transport time between forest landing and end-user is difficult to make more efficient given a specific route, if delays are excluded. On the other hand, time for loading material in the forest and unloading at the end-user is more open to influence. The cost response to changed activity times is plotted in Figure 19. Different loading times are often a result of local landing and windrow conditions, machine operator and work procedure. When unloading at industry, system SII unloads directly into a stationary crusher, whereas system SI just tilts the truck and trailer cargo space and side-tip the fuel onto the ground. Queues are sometime present at the industry, which makes unloading time highly variable. System SII was more sensitive to a change in load/unload time because its inferior transport capacity resulted in more round trips given the same amount of fuel to transport and thereby more load/unload processes. The plot of the cost effect of a change in load (cargo) volume showed that system SII was more sensitive due to its lower normal load capacity (Figure 19).

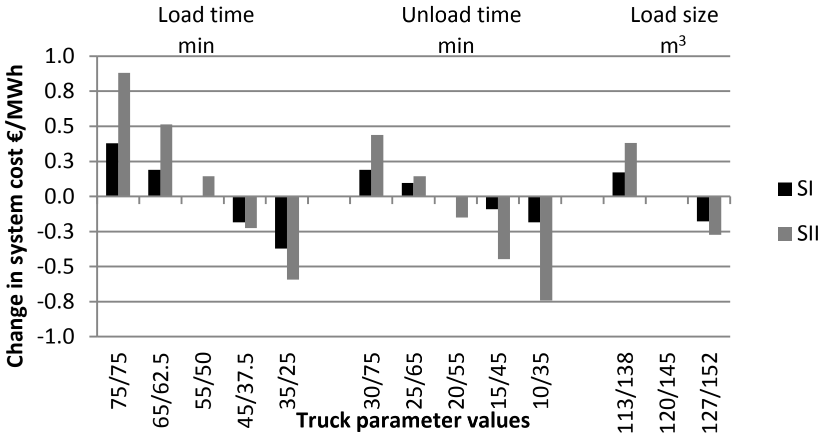

Figure 19 . Change in total supply chain cost due to different load/unload times and load sizes (cargo load) in systems SI and SII. When two values are given, the first is for system SI and the second for system SII. For a detailed description of these systems, see section 4.2.1.

5.2.5 Sieving of stumps at landing

Sieving can be seen as a way to achieve a more homogeneous fuel with less fine fraction and an assured quality. Rejecting 25% of dry mass through sieving and reducing AC from 20 to 5% meant that 11% dry mass on an ash-free basis ended up in the reject fraction. A fuel cost of 18.4 €/MWh was obtained when sieving of heavily contaminated material was tested. Transporting the same material directly to an end-user without comminution and sieving resulted in a fuel cost of 20.2 €/MWh. For comparison, the fuel cost for system SI and SII was 16.6 and 17.1 €/MWh, respectively, in the base case. Considering that sieving can shorten the required storage time, it becomes an interesting alternative.

5.2.6 Selection of study site

Not all areas are suitable for stump harvesting and many local factors affect the outcome. The initial amounts of stumps in the ground per site and road transport distance to the end-user are two factors that affect fuel costs.

The best system in different situations is shown in Figure 20. Site sizes of 75-300 odt of stumps per area and one-way transport distance from forest landing to end-user of 10-150 km were simulated. System SII's steeper curves with increasing transport distance emphasise its vulnerability to long transport distances due to the bulkiness of the fuel. The loose stump truck has an smaller load capability, which results in increased number of round trips. The smallest sites (75 odt) resulted in comparatively larger cost increases for both systems. System SI was more sensitive to small sites than system SII. Increasing the site size above 150 odt provided small cost decreases. A general pattern was evident, but since many parameters influence the results a change in one of these might result in a change, or at least, a tweak, in the cost curve, which is only valid for the conditions defined in this study. The parameter investigation in Paper II highlighted the result of changes in other supply chain-associated parameters.

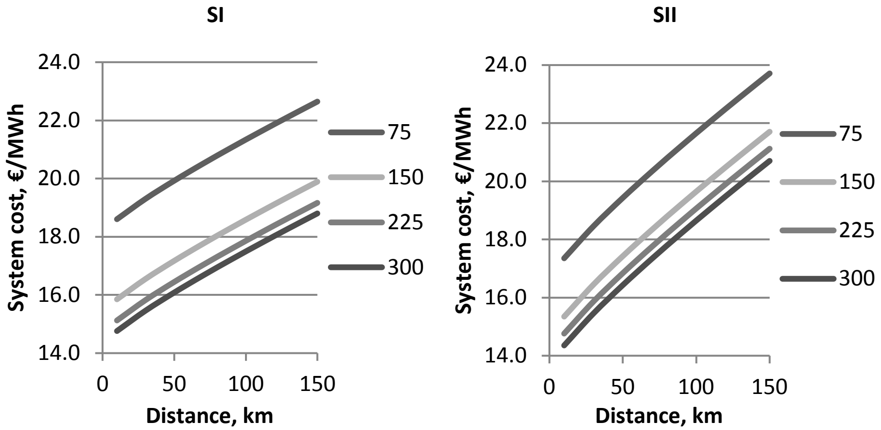

Figure 20. Cost influence of a change in transport distance (25-150km) and harvesting site size (75-300odt/site) for systems SI and SII. For a detailed description of these systems, se section 4.2.1.

5.3 General discussion of methodology

5.3.1 Model constraints and limitations

Discrete-event simulation was chosen as a study method since it is able to account for logistical interactions within systems. Simulation is an appropriate method when the modelled system has uncertainties and random elements, together with dependent activities and idle and queue times. Moreover, DES is convenient when making sensitivity analyses and studying different system configurations operating in different conditions (Thesen *et al.*, 1992).

Based on the simulations in Paper I and II, knowledge can be gained of system behaviour. The simulations were conducted in idealized cases regarding *e.g.* transport distances and fuel quality. By understanding the systems in those idealized cases, it is possible to apply that knowledge to actual operations.

In line with the definition of a model, the simulation models developed here were a simplification of the reality that proved accurate enough for the intended purpose. Simulation models contain two types of uncertainty: data uncertainty and model uncertainty (Anon, 2007). The data uncertainty type was estimated to be the dominant type in this thesis. The fact that stump fuel systems are unestablished and not thoroughly studied makes some form of data uncertainty inevitable.

Calculations for average speed based on the empirical equation developed by Ranta and Rinne (2006) were used for all truck transportation activities. In reality, the values are affected by the road conditions, the proportion of gravelled forest road and paved public roads, the truck and the operator, all of which varied between all situations studied. However, the general pattern for such an equation is assumed valid for all transport activities.

Oven-dry tonnes (odt) was used as a functional entity throughout in both models (Paper I and II). It means that the smallest stump unit considered was 1 odt and occasionally this implies some model weaknesses, since rounding off of uneven amounts sometime occurs. This entity is limited to discrete integer values. Odt was used for convenience, since *e.g.* kg would be impractical and would result in a slow simulation model.

Truck breakdowns and weather delays were not incorporated in the model. Backhauling was not considered either, even though it may sometimes be possible, at least for the longest distances and on a part of the route. The fact that the starting position of the trucks is at the end-user, and not at the trucking company, might have a minor effect on the results. However, during continuous operations this is not a problem. The payload and load capacity can vary significantly between different trucks. If another type of truck with other characteristics were assumed, different results might be obtained. Possible weather-related delays are estimated to be among the largest truck-related model constraints.

The hourly cost rate was not divided into separate components depending on work task performed, *e.g.* loading, driving or queuing for a truck. Instead an average cost was used for each machine, irrespective of work executed. This might result in an overestimate of the cost of idle machine time.

5.3.2 Input data

To account in the simulations for the variations in activity and process times frequently observed in real machine operations, different statistical distributions were used. Triangular distribution in particular was often used in this thesis, since it requires little process knowledge and is commonly used for models based on expert opinions. Model input is minimum, most likely and maximum values. Other similar studies have sometimes used uniform distributions for process times which implies that all values between min and max are equally likely (Mobini, 2011). If more data were available, distribution fitting software could be used to the real dataset, creating more realistic distributions.

One weakness in the input data is that a detailed dataset for breakdown and repair times of crushers was not available. Approximations from other studies and the characteristics of the process, together with approximations on average expected outcomes, were used to develop an input model.

Cost calculations have a central role, since the hourly cost significantly influences the monetary result. How the machine is expected to be utilised during a year greatly influences these calculations, *e.g.* whether the machine is used all year, seasonally, in one or several work shifts *etc*. Moreover, purchase price varies between different machine models and specifications. A challenge is to find comparable and consistent alternatives for all machines.

6 Conclusions

The main conclusions that can be drawn from this thesis are that:

- A system with comminution at the roadside landing and independent transport with a self-loading chip truck and trailer are always a good alternative, compared with the other systems, irrespective of study site conditions.
- Transport of uncomminuted stumps is cost-competitive for short distances.
- Systems with a high degree of machine dependencies must have a good balance in idle machine capacity to be cost-competitive. The comminution productivity, together with transport distance, strongly influences system behaviour, resulting in large cost variations.
- The most costly systems, almost irrespective of transport distance, are the chip truck system and the hook-lift truck system utilising only one transport unit, due to overcapacity in the crusher.
- Fuel losses late in the supply chain strongly influence system cost, whereas upstream losses are of less importance.
- Suitable storage, *i.e.* drying, can significantly reduce the whole supply chain cost. Avoiding fuel with MC >35% is crucial for system feasibility.
- Sieving stumps at the roadside landing in combination with comminution, hence enabling shorter storage duration and ensuring better quality, can be a feasible strategy.
- Selecting sites that allow machines to operate at high productivity is the most important factor affecting the fuel cost.
- Based on the results from the simulations and current fuel prices, a positive economic return is achievable.

- Discrete-event simulation and the logistics models developed where proved to be an effective tool for analysing the stump fuel supply chain.

7 Suggested further research

The simulation models developed here are mainly based on existing practices. Future technical developments might drastically change the supply chain, thereby making the results out-of-date. Examples of technical developments could be a new flexible and more mobile base machine instead of the excavators used today.

More field trials studying machines both separately and when working together are desirable. An increased understanding of the factors affecting machine performance is needed, since it greatly affects system cost. Reduced uncertainty and more predictable outcomes would help increase stump harvesting.

Today, there are still unanswered questions concerning the environmental issues relating to stump harvesting, such as locally reduced biodiversity and soil carbon balance. This is hampering stump fuel system implementation and new technical development in the area. General consensus among these questions is desirable and further research on these questions is thus essential.

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