Improving the Efficiency of Forest Fuel Supply Chains

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Abstract

Forest biomass has gained much interest as a resource for renewable energy production world-wide. In Sweden, easily accessible secondary forest fuels, such as by-products from the conventional forest industry, are today already fully utilised. There is still potential for expansion by greater utilisation of primary forest fuels, which consist of biomass previously left in the forest after logging, *e.g.* tree stumps and logging residues. However, to increase the volumes of these fuels, more cost-efficient supply systems must be developed to overcome strong price competition from other fuels. Since forest fuels are low-value goods, the profit margins are tight, resulting in low acceptance for inefficiency. Storage, comminution and transport are all required to deliver a product with acceptable quality when needed by the end-user. However, there are many ways to organise the supply chain, including use of different machines, strategies and forms of work organisation, which together result in numerous possible systems.

This thesis assessed the efficiency in forest fuel supply chains and sought to provide decision support on how, where and when biomass should be managed and handled to deliver a high-value fuel with low input of resources. Finding more efficient ways to organise the supply chain can lead to increased amounts of primary forest fuels being brought to market at a profit. For this, good decision support on which system to use in different situations and the consequences of different choices is needed. The methodology used in this thesis was discrete-event simulation and models of different supply chain alternatives were developed.

The results indicated that there is no such thing as a perfect system, but that each system can have its own niche. A hot system with a high degree of machine dependency must have a proper balance in machine capacity to be efficient. For transport and comminution, ensuring high utilisation of the comminution unit is key to increased cost-efficiency. There is a strong link between quality parameters and supply chain activities, which ideally should be planned with respect to present quality. It is possible to tailor fuel deliveries concerning quality by delivering the right biomass at the right time.

Keywords: Bioenergy, discrete-event simulation, supply chain, stump wood, logging residues, forest fuel, transport, comminution, modelling, fuel quality

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Dedication

To Catrine, Alma and Alvar

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., Hansson, P-A. & Jirjis R. (2014). Effects of supply chain strategy on stump fuel cost: A simulation approach. *International Journal of Forestry Research* 2014, ID 984395, 11.

II Eriksson, A., Eliasson, L. & Jirjis, R. (2014). Simulation-based evaluation of supply chains for stump fuel. *International Journal of Forest Engineering* 25(1), 23-36.

III Eliasson, L, Eriksson, A. & Mohtasami, S. Analysis of factors affecting productivity and costs for a high productive chip supply systems. Submitted.

IV Eriksson, A., Eliasson, L., Hansson, P-A., Sikanen, L. & Jirjis, R. Evaluation of delivery strategies for forest fuels applying a model for Weather-driven Analysis of Forest Fuel Systems. Submitted.

Papers I and II are 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 model used. Ran the simulation, 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 model used. Ran the simulation, interpreted the data and wrote the manuscript with input from the co-authors.

III Planned the study and developed the model together with the co-authors. Interpreted the data and assisted in writing the manuscript.

IV Planned the study with input from the co-authors. Developed the simulation model used. Ran the simulation, interpreted the data and wrote the manuscript with input from the co-authors.

1 Introduction

World-wide, more than 80% of the primary energy supplied in 2014 was fossil based. In order to break the fossil fuel dependency, a transition to renewable energy is needed. Bioenergy is currently contributing more to primary energy supply than any other renewable source, both in Sweden and worldwide (IEA, 2016; REN21, 2016; Anon, 2013a). Forest biomass has gained much interest as a resource for renewable energy production driven by concerns about climate change, fossil fuel dependency and an endeavour to produce more domestic energy (REN21, 2016; Björheden, 2012).

Bioenergy provides about one-quarter of the energy supply in Sweden and, since Sweden is a heavily forested country (57% being productive forest land (Christiansen, 2014)), the majority of the bioenergy produced is derived from forest. It is represented as a source in all main energy sectors (Anon, 2013a; Anon, 2013b) although the majority is used for heat and power generation and in the forest industry sector to generate process heat and power (Ericsson & Werner, 2016; Björheden, 2012).

In Sweden, space heating is a vital energy service due to the Nordic climate with its cold winters. The heating market is one of the dominant energy markets, with annual turnover of 10 billion Euros, and represents around 25% of total Swedish energy consumption. Energy-wise, district heating represents more than 50% of the heating market (Ericsson & Werner, 2016; Sköldberg & Rydén, 2014). Wood fuels represent the most important assortment in Swedish district heating (Anon, 2015c). Internationally, centralised district energy systems (heating and cooling) are also a steadily growing area of application today (REN21, 2016).

In Sweden, easily accessible secondary forest fuels, such as by-products from the conventional forest industry, *e.g.* bark and sawdust, are today already fully utilised (Björheden, 2012). Regarding primary forest fuels, which consist of biomass previously left in the forest after logging but now harvested for energy production, large-scale systems for collection of logging residues, but not stump wood, are in place (Routa *et al.*, 2013). Delivered volumes to district heating plants have increased steadily until recently (Anon, 2015a; Anon, 2015b) and can continue to increase, based on estimated potential for sustainable harvest (Claesson, 2008). However, in recent years increased competition from recycled wood fuels and household waste, both domestic and imported, has been seen (Anon, 2015a; Anon, 2015c).

To increase competiveness of primary forest fuels, many factors must be considered since the supply chain is more challenging and complex than that for many other products (Olsson *et al.*, 2016; Kanzian *et al.*, 2009; Gronalt & Rauch, 2007). Residues are harvested all year around as a by-product from conventional logging. However, demand at the district heating plants varies with season, with a sharp peak in winter. In addition, fluctuating outdoor temperatures lead to rapid short-term changes in demand (Werner, 1984). Storage is needed to buffer and cope with these fluctuations, but stored biomass faces bio-degradation problems and ties up working capital for the company (Jirjis, 1995). Moisture content can both increase and decrease during storage and the variations in quality mean that the monetary value is constantly changing (Sikanen *et al.*, 2012; Anerud & Jirjis, 2011; Pettersson & Nordfjell, 2007; Jirjis, 1995). Long storage periods are often needed to cope with both the demand situation and the quality specifications set by end-users. On the other hand, bioenergy provides a unique degree of freedom compared with other renewable energy sources, since storage is possible at different stages in the supply chain (Kanzian *et al.*, 2009; Eriksson & Björheden, 1989), potentially resulting in better control over production compared with intermittent renewable resources.

Heat and power plants often rely on a constant inflow of material (Olsson *et al.*, 2016), directly from the forest or from terminals, preferably in comminuted form. Forest biomass is a bulky material that is often comminuted at landing to facilitate transportation (Routa *et al.*, 2012), but comminuted material risks greater degradation problems during storage (Jirjis, 1995). If possible, comminuted material should therefore not be stored for long periods. This is a problem for forest biomass chipping and transport contractors and their employees, since much work can be expected at peak load times and little work is required in the summer.

Forest fuel is geographically dispersed in small concentrations all over the landscape (Kanzian *et al.*, 2009; Möller & Nielsen, 2007), so when designing supply chain this factor needs to be addressed since transportation is needed and the machines have to be relocated and re-established many times. Moreover, several different contractors are often in operation, working with linked activities affecting each other and ultimately the end results in terms of quality and cost. It has been shown previously that many collaborating units are challenging to organise and that it is important to reduce both queue time and idle machine time (Asikainen, 2010; Spinelli & Visser, 2009; Väätäinen *et al.*, 2005).

Since forest fuels are low-value goods, the profit margins are tight, resulting in low acceptance for sub-optimal alternatives. The logistical foundations are based on the following three activities: storage, comminution and transport, which are all required to deliver a product with acceptable quality when needed by the end-user. However, the order in which they are performed can change and there are many ways to organise the supply chain, including use of different machines, strategies and forms of work organisation, which together result in numerous possible systems. Each system can have its own competitive niche where it is superior to others (Björheden, 2008).

Cutting unnecessary costs within the supply chain is crucial to make the products more competitive. For forest fuels this is especially important, since the logistics costs constitute a major part of the total delivery costs (Brunberg, 2013; Routa *et al.*, 2012). Besides cutting costs, value creation in the supply chain might be an equally important aspect. In this regard, good quality management can improve the profit and strengthen the competitiveness of the products (Windisch *et al.*, 2015; Eriksson *et al.*, 2014a).

Finding more efficient ways to organise the supply chain can lead to increased amounts of primary forest fuels being brought to market at a profit. For this, decision support on which system to use in different situations and the consequences of different choices are needed. With deliberate choices with regard to supply chain design, input resources and expected storage outcome, more efficient supply chains can be accomplished.

2 Aim and objectives

The overall aim of this thesis was to assess the efficiency in forest fuel supply chains, in order to cut unnecessary costs and increase product value and system output. A secondary aim was to provide decision support on how, where and when biomass should be managed and handled within the supply chain to deliver a high-value fuel with low input of resources.

Specific objectives were to:

- Evaluate the influence of supply chain-related factors on the final delivery cost
- Evaluate the performance of machine systems for transport and comminution of stump wood
- Evaluate how work organisation and machine scheduling can affect system costs
- Develop a method and tool that consider dynamic quality changes during storage and can be used to plan and analyse delivery strategies.
- Analyse delivery strategies based on informed choices using the method and tool developed, with input of weather data.

3 Structure of the thesis

Supply chain planning can be carried out at three different levels of decision, *strategic*, *tactical* and *operational*, all involving different time horizons (Ba *et al.*, 2016; Ballou, 1992; Eksioglu *et al.*) Papers I and IV in this thesis are intended to provide decision support on strategic level, involving information that, when implemented, can result in benefits several years later. They also provide information related to *e.g.* resource allocation or inventory levels that are applicable from a tactical and operational point of view. Papers II and III are intended to provide decision support for more short-term decisions on tactical and operational level.

Three different ways of making the forest fuel supply chain more efficient are presented in the thesis. Paper I analyses 'what if' scenarios in all three areas. The first way is to cut the delivery costs, *e.g.* in €/MWh, through delivering forest fuels with less input of resources by utilising the machines in the system more efficiently (Papers II and III). The second way is to increase system output and reduce material losses (Papers III and IV). The third way is to increase product value by means of smart storage and better handling of end-user requirements (Paper IV).

This thesis deals with two different fuel assortments, stump wood (Papers I and II) and logging residues (Papers III and IV), as can be seen in Figure 1. Both are used to illustrate the function and potential for efficiency improvements within primary forest fuel supply chains in general and those two systems in particular.

Papers I and IV describe the full supply chain from forest to end-user. Papers II and III assess transport and comminution in more detail, as those two operations are unavoidable in the supply chain, have strong links to final delivery costs (Routa *et al.*, 2013) and can vary widely (Asikainen, 2010).

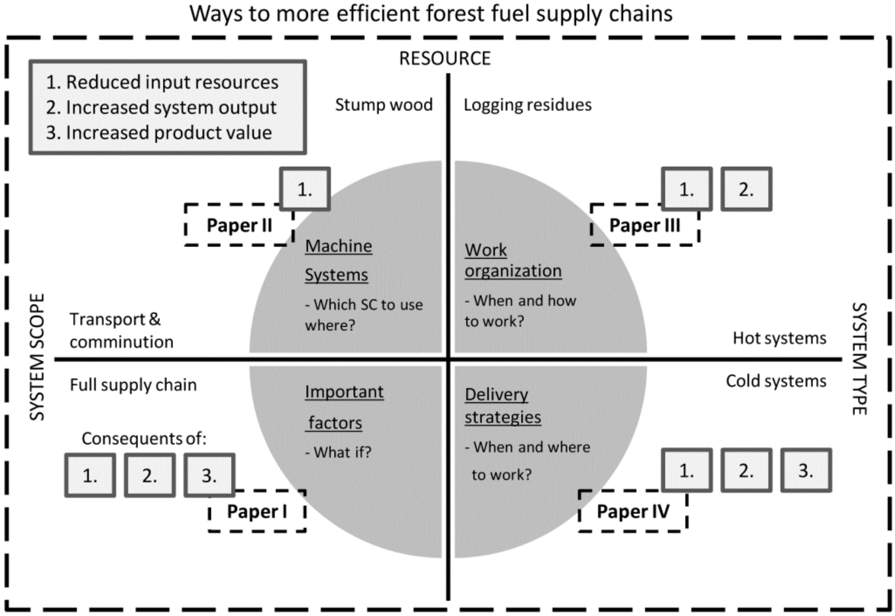

Figure 1. Schematic chart summarising how each paper (I-IV) in this thesis relates to the others and to the overall aim of the thesis. The numbers within squares indicate perspectives addressed in each paper (1,2,3) as listed in the top left-hand corner. System scope and system type are shown on the x-axis and type of resource on the y-axis. SC = supply chain.

3.1 Boundaries

The scope of the thesis was restricted to only considering systems for handling stump wood (Papers I and II) and logging residues (Papers III and IV) delivered directly from the forest to the end-user by trucks. This restriction excluded analysis of systems using terminals and other modes of transportation, *e.g.* goods trains or ships. However, this should not be taken to mean that terminals, trains and ships do not have a place within the forest fuel supply system. Moreover, a Swedish focus was adopted in the analysis and, as illustrated in Figure 2, the ultimate goal was fuel delivery to a heating plant or combined heat and power plant.

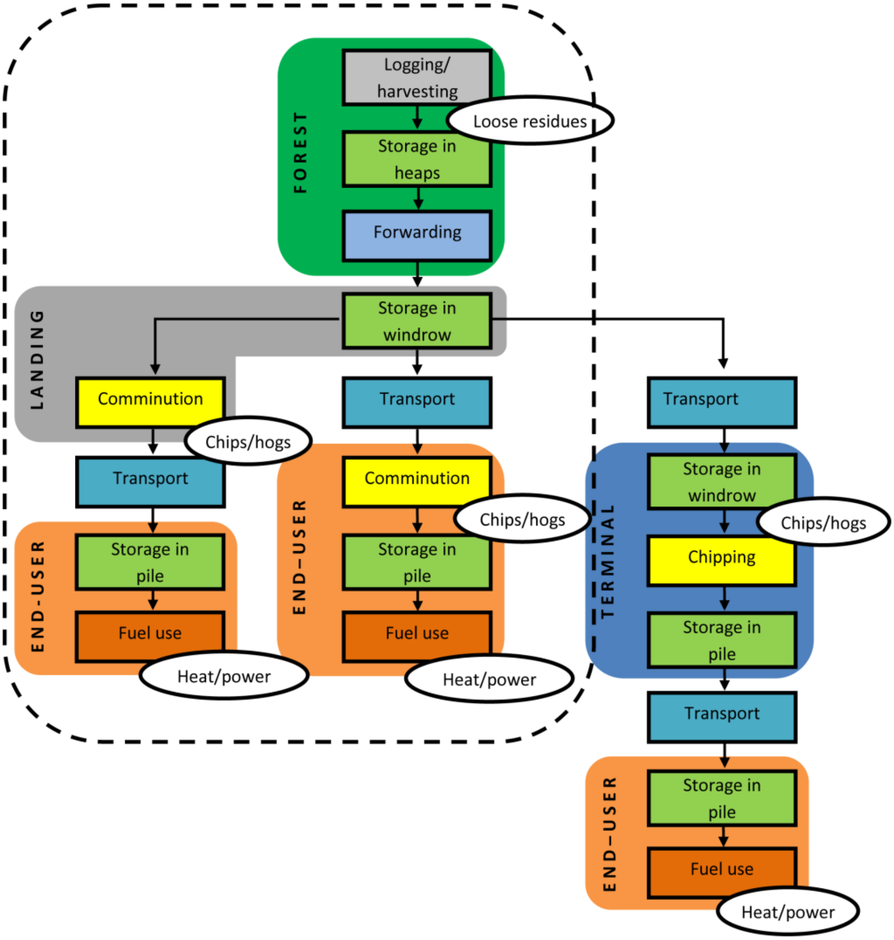

Figure 2. Schematic chart of activities and processes included in the thesis (within the dashed line) and activities excluded (outside the dashed line).

3.2 Other publications related to the thesis

During the work, on which this thesis is based, a number of other related areas were identified and investigated. The results of these investigations were published separately since it was not possible to fit all in the papers included in the thesis. However, since these publications fall within the subject area of the thesis, help meet the research aim and also provide additional information needed to understand the broader picture, they are listed below and cited elsewhere in the thesis when appropriate.

- Eriksson, A., Eliasson, L. & Jirjis, R. (2014). Simulation and modelling of wood chip container logistics at forest landings. Conference article, *in:* Bennet OY, ed. *Bioenergy from Forest 2014*, Helsinki.

- Olsson, O., Eriksson, A., Sjöström, J. & Anerud, E. (2016). Keep that fire burning: Fuel supply risk management strategies of Swedish district heating plants and implications for energy security. *Biomass and Bioenergy* 90(1), 70-77.

4 Background

4.1 District heating

In Sweden, district heating was almost exclusively based on fossil oil until the early 1980s, but concerns about excessive dependence on imported fossil fuels and later an increased focus on environmental issues in general, and climate change in particular, started a transition (Ericsson & Werner, 2016; Junginger *et al.*, 2005; Hillring, 1998). Today, fuel supply to district heating is dominated by different forms of woody biomass, waste and recovered waste heat (Figure 3) (Anon, 2015b). Primary forest fuel is important for wood fuel deliveries to district heating systems and, likewise, district heating is an important end-user for primary forest fuels today (Anon, 2015b; Björheden, 2012).

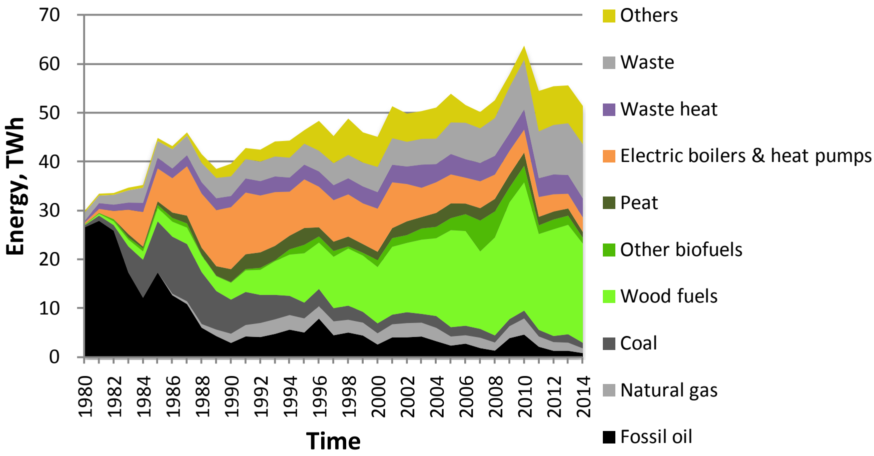

Figure 3. Changes in the supply of energy resources to Swedish district heating production in the period 1980-2014, based on statistics from the Swedish District Heating Association. Wood fuels include recycled wood fuels. Flue gas condensation is included within the 'Others' category.

District heating plants impose some constraints that today's primary forest fuel supply chains have to cope with. For example, limited storage areas, a bulky fuel and the associated storage problems create challenges in storing large quantities of forest fuels on-site (Olsson *et al.*, 2016; Jirjis, 1995). A typical Swedish heating plant has an on-site inventory of some 1-17 days of fuel use (Olsson *et al.*, 2016). Many larger Swedish plants lack stationary equipment for comminution, while operating semi-mobile comminution equipment at plants close to city areas is also problematic, due to *e.g.* noise and dust (Kanzian *et al.*, 2009). This means that most forest fuels need to be delivered in a continuous matter, in comminuted form, directly from the forest or from nearby terminals.

Trucks are the most common mode of transport and all heating plants receive fuels via trucks, although some also use other transport modes such as trains and ships in their fuel procurement system. Large plants can need up to 70 trucks per day at peak load times, resulting in potential queuing situations at the plant (Olsson *et al.*, 2016; Väätäinen *et al.*, 2005).

When studying deliveries of fuel to heating plants, it is important to bear in mind that the end-user and the supply system interact with each other. The demand at the end-user dictates conditions and sets specific requirements that the supply system must fulfil.

4.2 The primary forest fuel supply chain

The term *supply chain* in general refers to a structure with companies upstream and downstream linked through a flow of products and information from a resource to the customer (Christopher, 2005; Mentzer *et al.*, 2001). All companies involved add value and/or help bring the product to market. The purpose of the supply chain is to balance supply and demand (Christopher, 2005). The primary forest fuel supply chain starts with the resource in the forest and ends with a product used in heat and power production. It is unsettled whether the end-user should be part of the supply chain definition (Mentzer *et al.*, 2001), but in this thesis the end-user was included to some extent.

The work in this thesis also deals with the *value chain*, a concept first described by Porter (1985), as the value creation process extending from the raw material to the final consumer. However, this work only covered some activities that add value to the product, mainly those linked to operations and logistics, but not others such as sales and marketing. Since fuel quality is closely linked to the product value for forest fuels, this is a relevant concept to bear in mind when reading this thesis. There has been a shift in focus from reducing inputs to creating value (Asikainen, 2015; Hankin & Mitchel, 1994). Both active and passive activities within the value chain can affect the value of forest fuels.

Regarding forest fuels in Sweden, there has been a decrease in annual average fuel prices delivered at district heating plants during the last 5 year period (2011-2015) from 214 SEK/MWh (22.3 €/MWh) to 186 SEK/MWh (19.4 €/MWh) (Harrysson, 2015). The cost for logistics constitutes the major part (Brunberg, 2013).

4.2.1 Resource description

Primary forest fuels include biomass left after logging; this thesis deals with tree stumps and logging residues. The definition of a *stump* is 'the above-ground biomass below the merchantable stem, and its projection underground including the taproot' (Hakkila & Parikka, 2002; Richardson *et al.*, 2002). The wider concept *stump-root system* includes all roots (Richardson *et al.*, 2002), but in this thesis 'stump' is used as a generic name for the whole stump-root system. The definition of *logging residues* includes non-used parts left after the logging operations, such as tree tops, branches and unmerchantable stem wood (Eriksson & Björheden, 1989).

Globally, large-scale systems for extraction of primary forest fuels for energy are not widely established. Large countries such as the US and China have started investigating residue recovery after logging (Anttila *et al.*, 2015; Gan & Smith, 2006; Perlack *et al.*, 2005; Leinonen, 2004). The interest in recovery of residues from clear-cut areas started in 1970 and 1980 in Sweden and Finland (Nurmi, 2007; Andersson, 2000), although residues had been recovered earlier in history (Lundberg, 1915). Today, Finland and Sweden have systems up and running for large-scale logging residue procurement. Finland also has systems for stump harvest for energy purposes (Routa *et al.*, 2012). Stumps can be extracted for other reasons, *e.g.* to convert forest land to farmland, establish construction sites or prevent root rot diseases (Cleary *et al.*, 2013; Vasaitis *et al.*, 2008; Hudson *et al.*, 1994). In the Nordic countries, stumps of Norway spruce (*Picea abies* (L.) H. Karst.) 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) if the initially high ash content can be reduced (Anerud & Jirjis, 2011). The alternative to harvesting logging residues and tree stumps is to leave the material in the forest, resulting in decomposition over time (Ortiz *et al.*, 2016; Hammar *et al.*, 2015).

For thinning and final felling areas combined, a gross amount of roughly 140 TWh of logging residues and tree stumps could be recovered annually in Sweden. However, for final felling only, the gross potential is reduced to 93 TWh. This is reduced further to 59 TWh after the necessary ecological restrictions, and to 37 TWh when techno-economical restrictions are considered (Anon, 2008). However, to realise more of this potential the supply system must be efficient, since increased out-take usually means recovery of material from tougher objects, *e.g*. farther away from the end-user.

4.2.2 Quality aspects

For forest fuels, good quality can be defined as meeting customer requirements (Nilsson *et al.*, 2013). A number of parameters can be used to describe forest fuel quality: *heating value*, *moisture content (M)* and *ash content (A)* (defined according to EN ISO 17225-1:2014). *Mineral composition* and *particle size distribution* are other important parameters (Anerud & Jirjis, 2011; Gaur & Reed, 1995). Forest fuel is a bulk material comprising wood particles, water and air. Therefore, *bulk density*, which is the ratio of weight to loose volume, *solid volume content*, which describes load occupancy, and energy density, which is the ratio of amount of energy to loose volume, are important (EN ISO 17225-1:2014). In general, end-users values homogeneity (Nilsson *et al.*, 2013).

It is important to bear in mind that these quality parameters are affected by time and the activities within the supply chain. Conversely, the quality parameters can affect the performance of supply chain activities. The product value of a forest fuel is a function of the amount of material and its quality parameters.

About half the weight in fresh woody material consists of water, which is unwanted since it needs to be evaporated when the biomass is combusted, which requires energy (Pottie & Guimier, 1985). In a transportation perspective, it is also unwanted since transport of unnecessary water is resource-inefficient. Moisture content is often referred to as the main quality parameter, as it has a large impact on delivered energy, which is the basis for financial transactions between the actors involved. Wood is a hygroscopic material and the moisture content is affected by the handling and storage after harvesting and can both increase and decrease driven by *e.g.* the ambient weather (Richardson *et al.*, 2002; Haygreen & Bowyer, 1996; Hakkila, 1989). In general, dry forest biomass is composed of cellulose, hemicelluloses, lignin and a small amount of extractives and minerals (Gaur & Reed, 1995). The dry matter can be reduced due to mechanical losses of material or by bio-degradation caused by microbial activity (Jirjis, 1995). Ash is a by-product of the combustion process and is derived from both (naturally occurring) minerals in the wood and impurities (both organic and inorganic contaminants) (Thörnqvist, 1985). The amount of ash derived from impurities varies considerably and is highly affected by procurement and handling methods throughout the supply chain. For stump wood, a large part of the stump grows below ground, resulting in unavoidable soil contamination (Anerud & Jirjis, 2011). The mineral out-take through the extracted forest fuels should ideally be compensated for by returning ash to the forest, thereby avoiding problems with nutrient depletion.

The heating value depends on chemical composition of the material and it varies between species, materials and tree parts (Anerud & Jirjis, 2011; Nurmi, 1997).

The particle size and particle size distribution of the material affect the combustion process, fuel handling properties and also bio-degradation (Pottie & Guimier, 1985).

4.2.3 Hot and cold systems

When studying supply systems, a distinction is made between hot and cold systems. In cold systems, material is stored between operations, and thus there are no direct interactions between machines. In hot systems, no material is stored between the operations, which leads to interactions between the machines in the system. Hot systems are sensitive to imbalances and there is a greater risk of machines being left in an idle state waiting for another one in the system. Chipping material directly into a truck is an example of a hot system where transport and chipping capacity must be matched to avoid unnecessary idle time (Eriksson *et al.*, 2014b). Several studies have highlighted the importance of balancing machine capacities to avoid unnecessary costs caused by unutilised machines in hot systems (Karttunen *et al.*, 2012; Väätäinen *et al.*, 2005; Asikainen, 1995; Bradley *et al.*, 1976).

4.3 Supply chain activities

Forest fuel systems have some activities in common irrespective of the material handled. The focus in this section is on the activities and their connection to forest fuel efficiency, regardless of whether it is to increase value or to cut unnecessary costs through better use of the input resources. Moreover, how quality affects each activity, and *vice versa*, are described.

4.3.1 Harvesting and forwarding

Primary forest fuels are merely a by-product of conventional roundwood harvest. Other market forces than bioenergy related ones influence availability and timing of harvest (Richardson *et al.*, 2002). In logging residue systems, there is no harvesting cost for the material, *i.e.* there is no extra cost for the fuel-adapted logging operation where the material is directly placed in harvester heaps on the cutting area compared with conventional harvesting operations (Nilsson *et al.*, 2015). Stump fuel systems need an extra activity, stump harvesting, to mechanically uproot and make the biomass accessible for later supply chain activities. The general technique uses a large-scale (around 20 tonnes) tracked excavator equipped with a stump-lifting head that uproots, splits and shakes the stumps to get rid of soil contamination (Kärhä, 2012; Laitila *et al.*, 2008). This is one reason why supply costs can be higher for the stumps (Routa *et al.*, 2012).

Both logging residues and stump wood have some initial quality characteristics that the downstream supply chain activities has to work with. Logging residues are harvested all year round, but in general more logging takes place during the autumn and winter compared with the spring and summer season. 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).

After a short storage period, forwarding is the next activity, which comprises collecting and transporting the material to a landing, close to or at roadsides, where the material is preferably accessible for trucks. Forwarding of forest fuels is possible all year round in favourable conditions. However, forwarding operations during winter are limited. The time taken to forward forest fuels is mainly dependent on the distance, the terrain, load size and clear-cut area conditions (Laitila *et al.*, 2008). Moreover, the amount of the gross biomass that can be recovered varies depending on the operator's skill, site conditions, condition of the heaps, time spent and proportions of the harvested biomass that are found and collected, meaning that some biomass remains in the cutting area (Nilsson *et al.*, 2015; Nordström *et al.*, 2012; von Hofsten *et al.*, 2012a). After operation at one site, the forwarder or excavator has to be relocated, often using a lowbed-trailer, to the next site.

Machine productivity, lost material and quality of the material produced affect the final supply cost. If *e.g.* the driver is careless and takes material too close to the forest floor, the ash content can be increased as a consequence of soil contamination.

4.3.2 Storage

Storage is necessary for production and for demand-related, quality-related and energy security reasons. The fluctuations in demand make deliveries in a just-in-time manner too vulnerable. Storage is needed to cope with instant demand and production variations and fluctuations in both the short and long term (Laihanen *et al.*, 2013; Gold & Seuring, 2011).

Storage changes the biomass in several ways and the dry matter can be reduced due to mechanical losses or losses caused by microbial degradation. Moreover, water in the material can be both increased and decreased, as can the ash content due to contaminants falling off or getting mixed into the material. Material composition can also be changed due to *e.g.* needles falling off (Anerud & Jirjis, 2011; Nurmi, 1999; Jirjis & Lehtikangas, 1993). The ultimate goal is to deliver as much dry matter with as low moisture and ash content as possible. This makes storage an important activity within the supply chain, since it influences these parameters.

The storage process is similar in terms of where and how to store stump wood and logging residues, although details can differ. The first storage phase starts directly after stump harvesting or the logging operation where the biomass is placed in heaps on the cut area. The Swedish Forest Agency recommends leaving logging residues for one summer at the regeneration area to facilitate drying and defoliation, thus redistributing nutrients back to the soil (Anon, 2007b). The material is sometimes forwarded to the landing directly, or after a very short period in heaps, for practical reasons.

The next storage phase is in windrows, often next to the forest road. For logging residues, after being piled up by the forwarder, the biomass is often covered with cardboard to reduce the effects of snow and rain penetrating the windrow and increasing moisture content (Pettersson & Nordfjell, 2007). For stump wood, rain can be positive as it can clean away contaminants (Anerud & Jirjis, 2011). The material is stored until it is requested by a heating plant or transported to a terminal.

The next possible storage point in the supply chain is at terminals and at district heating plants, both in comminuted and uncomminuted form. Storage time at the heating plant is often relatively short, at least if the material is comminuted (Olsson *et al.*, 2016), whereas storage at terminals can be for longer periods (Virkkunen *et al.*, 2015). Storage-related problems are more prevalent in piles of comminuted materials due to the larger exposed surface area and problems with heat dissipation, which create a beneficial environment for microorganisms (Jirjis, 1995). Storage is negative for the dry matter content, as losses caused by microbial degradation can reduce the amount of fuel over time

Storage can increase product value without active input. For stump wood, reducing the unacceptably high ash content in newly harvested stumps, caused mainly by attached soil contaminants, is necessary and is a strong driver for storage. Rainfall can rinse contaminants away (Anerud, 2012; Anerud & Jirjis, 2011). Logging residues do not struggle with problems of too high ash content, at least if handled properly in earlier supply chain activities.

In both heaps and windrows, moisture content can change quickly driven by *e.g.* evaporation and precipitation. The variations can be large due to differences in weather conditions, but a general pattern with drying during spring-summer and rewetting during autumn is common (Anerud & Jirjis, 2011; Laurila & Lauhanen, 2010; Lehtikangas & Jirjis, 1995; Jirjis & Lehtikangas, 1993). During the winter, little or no drying takes place (Sikanen *et al.*, 2012).

4.3.3 Comminution

Comminution means size reduction of the biomass and it converts the material into an acceptable fuel fraction that is manageable for the internal fuel handling system of the end-user. It improves transport properties due to higher bulk density and facilitates an efficient combustion process through higher homogeneity (Eriksson *et al.*, 2013; Pottie & Guimier, 1985).

Comminution can be performed at any location between the source and the consumer (Eriksson & Björheden, 1989). The increased load density of bulky assortments, *e.g.* logging residues, requires this activity early in the supply chain (Björheden, 2008). However, the reduced storability after comminution requires it to take place as close in time to the energy conversion process as possible. Due to economies of scale, comminution downstream in the supply chain using larger machines is often cheaper (Kanzian *et al.*, 2009).

The different comminution techniques used for forest biomass include chipping, grinding and shredding. A chipper uses sharp tools to cut the material into regular pieces and thus a clean material is needed. The other techniques use blunt tools to smash, tear or crush the material. Grinders and shredders can better handle contamination, but produce inferior and more irregular quality with *e.g.* long slivers (Hartmann *et al.*, 2006; Pottie & Guimier, 1985). Due to the presence of soil contaminants, it is necessary to use grinders and shredders for comminution of stump biomass (Goldstein & Diaz, 2005). Logging residues are often comminuted with chippers (Routa *et al.*, 2012).

The performance of comminution units varies considerably, depending on comminution technique, engine power, working conditions, operator and ingoing material (Eliasson *et al.*, 2012; Röser *et al.*, 2012; Spinelli *et al.*, 2012; Spinelli & Magagnotti, 2012; Kärhä, 2011; Pottie & Guimier, 1985).

The biomass can be comminuted in the terrain, at road-side landings, at terminals or at end-users, using mobile, semi-mobile and stationary units (Wolfsmayr & Rauch, 2014; Kärhä, 2011; Hakkila, 1989). In Sweden, 90% of the logging residues are comminuted at the landing before transport. The remaining 10% are comminuted at a terminal or at the end-user, using larger machines that are sometimes of a stationary type (Routa *et al.*, 2012). In Finland, stumps are generally comminuted at a terminal or at the end-user, using semi-mobile or stationary machines (Kärhä, 2011).

Chippers are often mounted on *e.g.* a forwarder or a farm tractor trailer. Recently, chippers mounted on a chip truck, forming a *chipper truck* unit that can both transport and chip material, have gained popularity (Trolin, 2013). A mobile comminution unit mounted on a truck or trailer is fairly easily moved between job sites. Larger units may require a separate machine trailer.

Comminuted biomass at the landing is either deposited on the ground or directly into trucks or containers (bins). Moreover, some systems sieve the material already at the landing, aiming for higher quality by separating a reject fraction from an accepted fraction, but these quality improvements are achieved at the expense of some material losses in the reject fraction (von Hofsten & Brantholm, 2013; Fogdestam *et al.*, 2012; von Hofsten *et al.*, 2012b; von Hofsten & Granlund, 2010).

4.3.4 Transportation

The cost of transportation is significant in the forest fuel supply chain, due to the often high moisture content, low bulk and energy density, high bulk volume and non-uniformity of the material (Wolfsmayr & Rauch, 2014; Kanzian *et al.*, 2009; Stokes *et al.*, 1993). Production sites are 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 creates a need for transportation for the resource to reach the end-user. In 2010, the 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, and occasionally even longer, have been reported (Andersson & Frisk, 2013). Uncomminuted material is in general transported shorter distances than comminuted material, but both are still restricted to local and regional markets. Other modes of transport must be applied, *e.g.* train or ship, for long-distance transport (Tahvanainen & Anttila, 2011).

In general, biomass transport efficiency, productivity and cost depend on the form in which the biomass is transported, the vehicle used, bulk density and the moisture content. Each form may require certain vehicle types and methods for loading and unloading (Pottie & Guimier, 1985). Transportation of wet fuels is resource-inefficient and a drier material in general means that more energy can be delivered with the same trucks. Moreover, a moist material causes handling problems during cold weather, due to material freezing (Pottie & Guimier, 1985).

In Sweden, forest fuel transportation by truck is in general restricted to a maximum gross vehicle weight (GVW) of 64 tonnes governed by national legislation. 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). A low solid volume content, *i.e.* low load occupancy, results in inefficient resource utilisation with difficulties in achieving maximum payloads and ultimately more expensive transport (Ranta, 2002). The truck load is limited either by volume or by weight through the volumetric limitations or the maximum payload. In general, loads with low solid volume content and low to medium moisture content are limited by volume, while compacted loads with high moisture content are often limited by weight (Wolfsmayr & Rauch, 2014; Hall, 2009; Ranta & Rinne, 2006; Talbot & Suadicani, 2006; Johansson, 2000).

In Sweden, five main types of transport vehicle are used for forest fuel transport (Mortazavi & Johansson, 2013; Trolin, 2013; Liss, 2006b; Ranta & Rinne, 2006; Johansson, 2000):

- A light-weight vehicle for bulk transport of comminuted material, such as a chip truck and trailer or semi-trailer configuration
- A chip truck and trailer combination equipped with a crane with a clamshell bucket for self-loading
- A hook-lift truck and trailer system with different sets of interchangeable containers, which enables re-filling at the landing when the truck is elsewhere
- A high-volume truck and trailer for loose residue transport, equipped with crane and grapple for self-loading
- A chip truck and trailer with a mounted chipper or crusher where fuel is discharged via a conveyer belt or blown into the load space.

In addition, logging residues can be transported as compacted bundles using timber trucks but this system has practically disappeared in Sweden (Routa *et al.*, 2012). Mounting a crane on a chip truck decreases cargo space and payload but makes the system less hot, as it enables chips to be stored on the landing (Liss, 2006a). A system loading material from the ground loses some material closest to the ground and imposes a risk of incorporating contaminants into the biomass, leading to higher ash content (Liss, 2006a). A mounted unit for comminution drastically reduces both cargo space and payload (Trolin, 2013), but reduces machine interactions and improves chipper relocation.

4.4 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). When studying a system, it is possible to examine either the actual system or a model of the real system. A *model* can be seen as an abstraction of the real world with a sufficient level of detail for the intended purpose. There are both physical and mathematical models. The mathematical models can be solved using either analytical methods or by simulation. *Simulation* is the process of conducting experiments with a model for the purpose of understanding the behaviour of the system over time and/or evaluating strategies for the operation of the system. 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 (Law, 2007; Banks, 1998). When complex systems are studied, analytical equations describing the system state can be difficult to derive (White & Ingalls, 2009).

In numerical modelling, it is possible to work with performance evaluation with *e.g.* simulation or work with optimisation. When simulation models are run, a number of scenarios and inputs are often tested and the system behaviour is recorded. A recommendation for a good solution can be given and the consequences of implementing other solutions can be described. Optimisation, on the other hand, can search for and provide an optimal solution given some conditions. However, development of faster computers has enabled simulation of more sequences of run and system configurations and variable set-ups (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 dynamic and often stochastic, an approach that is suitable if randomness is expected and system studies over time are desirable (Banks *et al.*, 2010; Law, 2007). Different paradigms and concepts are available in discrete-event simulation, but a general structure exists among different simulation software products. *Inputs* are used to communicate with the model. A collection of *system state variables* holds all the information needed to describe the discrete-event system at a specific point. In discrete-event simulation, 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. If 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 without interfering with the real system. Frequently mentioned strengths of the discrete-event simulation method are its flexibility, versatility and analysis potential (Ryan & Heavey, 2006) and it is frequently used as a decision support tool (Banks *et al.*, 2010; Law, 2007). The possibility to account for interactions between processes and effects of random events, *e.g.* random machine breakdown, together with the possibility to include distributions describing events and timings, make discrete-event simulation a strong tool when mimicking real life processes. Bottlenecks and important factors can be identified. It is an appropriate method if dependent activities exist and idle and queue time occurs. Moreover, discrete-event simulation is convenient when making sensitivity analyses and studying different system configurations operating in different conditions (Thesen *et al.*, 1992). Other advantages with the method are the animation and visualisation provided by most software packages, which provides great possibilities for system discussion and evaluation. It also helps when communicating the model with *e.g.* stakeholders, as they can see what is happening within the system. The behaviour of the system can be monitored throughout the simulation, and not just the end results. In new and/or large physical systems, the results are often obtained more cheaply than with field studies, since no material acquisition is needed for setting up the system and 'what if' questions can be answered without building the real system (Banks *et al.*, 2010; Law, 2007).

Discrete-event simulation is used for tactical, operational and strategic planning in logistics and transportation systems when studying movements of physical goods (Banks, 1998). It is often used for problems on the operational level, and optimisation more often on the strategic level (Ba *et al.*, 2016). One frequently mentioned key area suitable for discrete-event simulation 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). Similar problems as examined in this thesis were solved with discrete-event simulation in the US back in the 1970s (Bradley *et al.*, 1975). The methodology has thereafter been used successfully in many biomass supply chain and logistic studies (Mobini *et al.*, 2013; Karttunen *et al.*, 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).

5 Methodology

Four different models were developed in this thesis, one in each of Papers I-IV, using discrete-event simulation.

The focus was on efficiency in forest fuel supply chains from different perspectives. The methodology developed, the scope of each model, the systems design and the experimental design are described briefly in this chapter, but for more detailed descriptions see Papers I-IV.

In each paper, a representation of the selected machine systems was modelled. One or several objects were created to act as fictive study sites in which the supply systems could be examined while handling biomass. The flows of resources (*e.g.* a machine) and items (*e.g.* units of biomass) were modelled through a number of interlinked activities. Probability distributions created stochasticity in *e.g.* process times and machine break-downs. Biomass was transported through the structure by machines circulating within the models. The dynamic models kept track of the time for each entity in each activity in the system, irrespective of whether it was *e.g.* queue time, waiting time or operating time. The models recorded delivered fuel, time consumption for each activity, cycle time, machine utilisation rate and total accumulated cost of each activity. 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).

The models used in Papers I, II and IV belong to a family of models that are structured in a similar way. These were all based on an approach whereby a set of objects was generated, each with a location and a specific amount of available biomass, and later delivered to one single end-user using different modelled machine systems. Each object also had a specified quality which was stored in each object's attribute. Simulation was executed with machine systems running in parallel handling the same set of objects. When one object was finished, the machine system was relocated and started to work at the next object. Each machine system was constructed as a linked logic of activities and distinct work tasks needed for fuel delivery. The actual capacity of each truck load was calculated based on the parameters associated with each fuel entity and the specification for the truck (cargo space and allowed payload).

5.1 Methodology developed in Paper I

In Paper I, two different stump fuel supply chains starting with tree stumps in the ground were assessed. Two cold systems using self-loading trucks for transportation were considered. One of the supply chains studied (SI) included crushing at landing and transportation of hog fuel, while the other (SII) included transport of stump pieces which were crushed after transport. Both included stump harvesting and forwarding before the later activities. The systems included were similar in structure and therefore easy to compare.

The model is programmed to enable variation (fixed or stochastic) of 15 pre-defined study factors. 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. The simulation model calculates the amount of energy delivered and the input to the system in terms of machine time and cost.

Sensitivity analyses were used as a tool and the simulation experiment focused on the effect on cost when varying the study factors at fixed levels. Factors associated with fuel quality, machine performance, object location and size, and losses at different phases were evaluated. A base case and a low and high level were defined for all factors, but still within a range commonly seen in practice. By assessing two cold systems, it was possible to examine the importance of factors within the supply chain without having to consider interference from effects caused by imbalanced systems.

5.2 Methodology developed in Paper II

Four main systems for transport and comminution of stump wood (henceforth referred to as S1, S2, S3 and S4) were identified and evaluated in Paper II. 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). Systems S2 and S3 were based on direct loading, thus forming a hot system, whereas the other two used self-loading from the ground. The general system classification is shown in Figure 4 and a sketch of the systems is provided in Figure 5. A buffer of three containers at the landing was used in system S3.

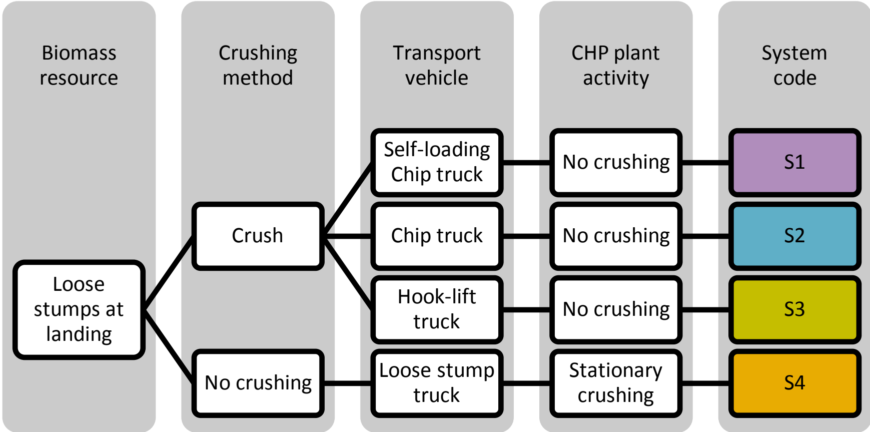

Figure 4. Flowchart showing the system code and the main processes involved in each system studied in Paper II.

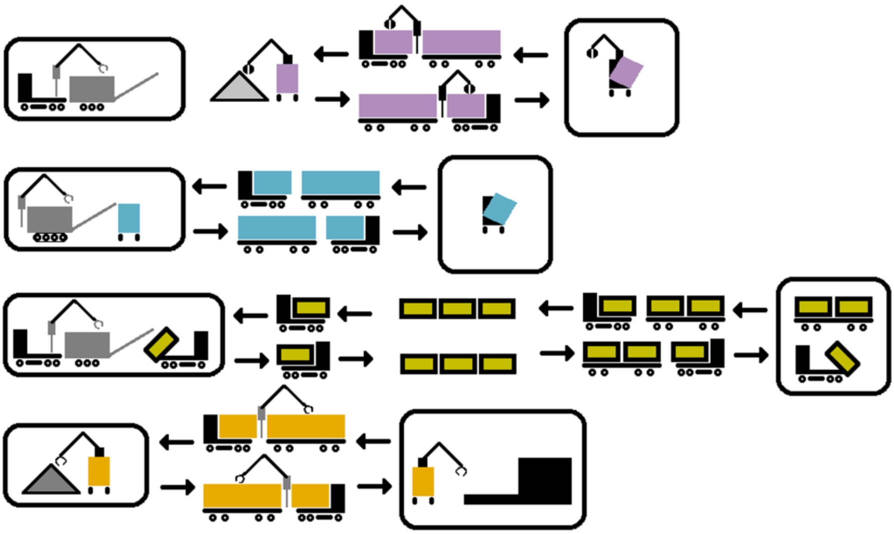

Figure 5. Sketch showing (top to bottom) systems S1-S4 in Paper II. Activities in boxes on the left represent comminution and loading at the landing, the processes in the centre of the diagram are transport, and activities in boxes on the right represent unloading and fuel delivery at the end-user.

Besides all four main systems (S1-S4), configurations with one, two and three trucks were simulated for the hot systems (S2 and S3). The one-way transport distance was handled as an experimental factor, with six discrete levels (25, 50, 75, 100, 125 and 150 km). Each simulation run included handling of multiple objects during a long period and five replications were conducted.

5.3 Methodology developed in Paper III

A system with a large and highly productive forwarder-mounted chipper, chipping logging residues into containers, was studied. A model was developed to study coordination between the chipper unit and the chip trucks transporting the chips produced. A hook-lift equipped forwarder was included as a link between the chipper and the transport trucks. It shunted containers between the chipper and the transloading point, where containers were later transloaded onto trucks (Figure 6).

Simulations were carried out to examine how shift scheduling and chip buffers affected the system costs and system output.

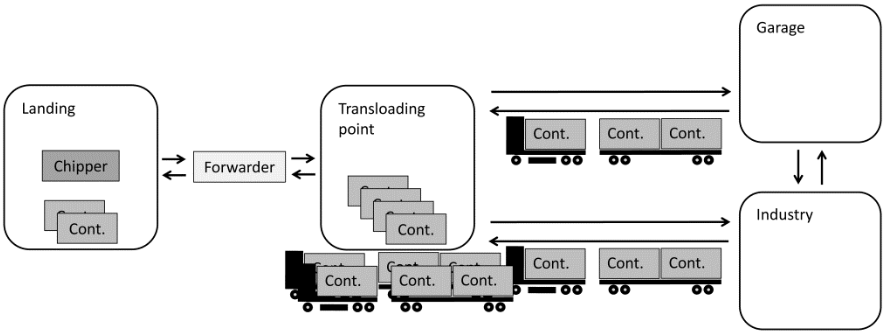

Figure 6. Sketch showing the machine and material flows studied in Paper III, where materials are moved in containers (Cont.) to their end-use at a heating plant (Industry).

The model was constructed based on experiences from a field study of a similar system (Eliasson *et al.*, 2013). It is programmed to cover machines scheduled to operate one shift during one working week of operation. The trucks start and end every day in the garage and, as long as there are containers filled with biomass to retrieve and sufficient time left of their shift, they go for another round trip. If little time is left when the truck returns, it can park loaded in the garage and start the next day by going to the end-user.

The experimental set-up involved two different buffer sizes of containers (three or six containers) and two shift scheduling regimes for the trucks (simultaneous or staggered). In the staggered shift, the trucks started at one-hour intervals in the mornings, instead of simultaneous. Two, three and four trucks were evaluated and in different environments. Ten replications were carried out.

5.4 Methodology developed in Paper IV

In Paper IV a new methodology was developed for studying forest fuel supply chains. It considers both passively achieved quality and value changes during storage, driven by weather data, and active machine activities when handling logging residues at different locations. It also enables evaluations of strategies for supplying an end-user with a weather-driven diachronic fuel demand and its consequences for the production system.

Unlike the approaches used Papers I-III, which started with one or several objects, the model developed in Paper IV considers objects continuously being pushed into the model randomly, but with a seasonally cyclic pattern. Objects are then both pushed and pulled to the district heating plant, where the biomass from the objects leaves the model after being combusted at a rate determined by weather data. Chipper trucks try to meet this demand with the help of an on-site inventory. Two types of truck lines are programmed, one always trying to push chips to the plant (ordinary truck line) and one that starts to work when the inventory levels at the plant fall below a critical limit (extra demand-driven truck line).

The model is constructed as a combined push and pull structure with six different modules: *create objects*, *storage in heap*, *forwarding*, *storage in windrow*, *transport and comminution* and *end-user* (Figure 7). Everyday new fuel quality values are set for the objects stored in windrows and heaps, and material is also deducted to account for dry matter losses. Fuel quality changes included are driven by empirical equations and weather data (Erber *et al.*, 2014). After each day, there is a possibility to actively sort all objects based on a predefined criterion, *e.g.* driest first, thus creating a priority for downstream activities.

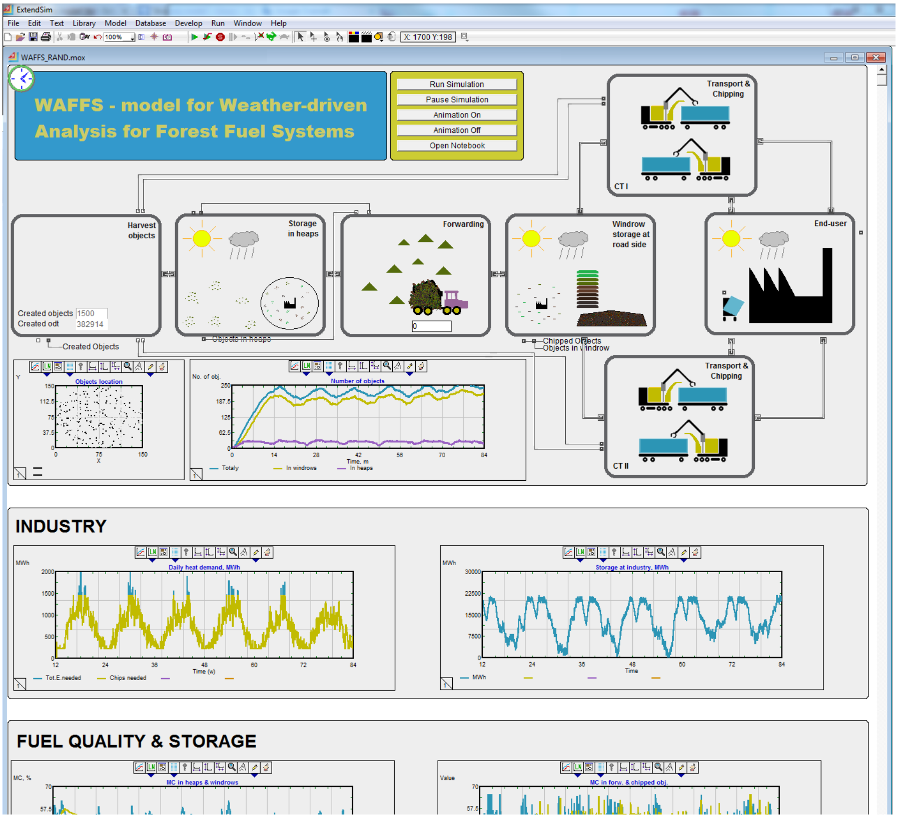

Figure 7. Screenshot from the model developed in Paper IV.

A terminating experiment during five heating seasons starting 1 July 2003 was carried out. A warm-up period of two years was used to create an initial set of objects in different phases and apply a delivery strategy to those before the simulation and data collection started. Each object created was randomly placed within a circle around the industry with a radius of 75 km.

Four delivery strategies were developed and evaluated with respect to machine utilisation for the chipping and transport contractor and delivered quality. The first strategy used no information and just handled the objects in a random manner (R – random). The three other strategies made deliberate decisions based on knowledge of storage time, quality and location of each object. The second strategy (FT – fast track), previously referred to as the fast track supply chain (Kinnunen, 2016), delivered material as fast as possible during summer (prioritising short storage time) and material being stored for longer times during winter. The third strategy (Q – quality) prioritised based on quality and tried to deliver dry material in winter and more low quality material during summer. The fourth strategy (L – location) tried to deliver material from more distant objects in summer and the oldest during winter.

5.5 Simulation input data

Hourly machine costs used in the simulation models were based on both approximations and calculations from costing templates (Ackerman *et al.*, 2014; von Hofsten *et al.*, 2012a; von Hofsten, 2006). The calculations were net cost calculations from the contractor's point of view and excluded *e.g.* profit, risk 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 were available, probability distributions were fitted to the data, but since some of these systems are new and sometimes unstudied, other information, such as expert opinions or physical properties, were occasionally used as a basis for the input modelling.

5.6 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. In modelling, the first step is to observe the system and discuss it with people familiar with it. The second step is to develop a conceptual model based on how the system is interpreted. The third step is to implement the conceptual model in a computerised environment (Banks *et al.*, 2010). Sargent (2013) describes the following four aspects of validation and verification: *Conceptual model validation*, defined as determining that the theory and assumptions used when developing the mental model are reasonable for the intended purpose of the model; *computerised model verification*, defined as assuring that the model is programmed and implemented correctly with respect to the conceptual model; *operational validation*, defined as determining that the model output behaviour has sufficient accuracy for the intended purpose; and *data validity*, defined as ensuring that the data used in model building, evaluation and testing are adequate and correct. Validation and verification are integral parts of model development and most techniques used are based on informal and subjective comparisons (Banks *et al.*, 2010).

Model validation serves two purposes: a) to produce a model that captures true system behaviour closely enough for decision-making purposes; and b) to increase the credibility to an acceptable level so users can be confident when using the model results. However, no model is a correct representation of the system and whether a model is valid or not depends on expectations and needs.

All models in this thesis were validated and verified using similar approaches. The conceptual models and their logic were discussed with people knowledgeable within the real systems, to anchor core assumptions and ideas. In the verification process, structured walkthroughs, comprehensive test runs and debugging were used to review system code. Since a dedicated simulation language was used, fewer errors can be expected than if a general programming language had been used. Animation was used to assure operational validation by studying system behaviour during model execution. Specific items were followed and traced within the model and data were continuously checked to assure proper logic. Different performance measures were also visualised and studied during simulation. To assure high face validity, all models were also discussed with respect to behaviour and output data with people familiar with the real systems. When possible, output data were also compared with data from field studies and simulation studies, to assure realistic patterns. However, a full cross-validation with real-world data was impossible due to practical and economical issues.

All models used were found to be reasonable based on those tests and evaluation techniques. More information about these methods can be found elsewhere (*e.g.* (Sargent, 2013; Banks *et al.*, 2010; Balci, 1994).

6 Results

6.1 Identifying areas for improvement

As a starting point, two cold systems for stump fuel were assessed, including the whole supply chain from the forest to the end-user (Paper I). The two systems, SI and SII, differ at a fundamental level, as the first comminutes biomass at the landing and the latter after transport.

Running the supply chain model with all study factors at their base level resulted in a delivery cost of 16.6 €/MWh for system SI and 17.1 €/MWh for system SII. The experimental frame of the study, when all factors simultaneously were at their low and high level respectively, ranged from around 10.5 to 30 €/MWh, irrespective of system. Such large variation in cost indicates potential for major cost reductions, but at the same time a risk of unnecessarily high delivery costs. On analysing the source of the costs by studying cost components, it was found that all machines included made important contributions to the costs (Figure 8).

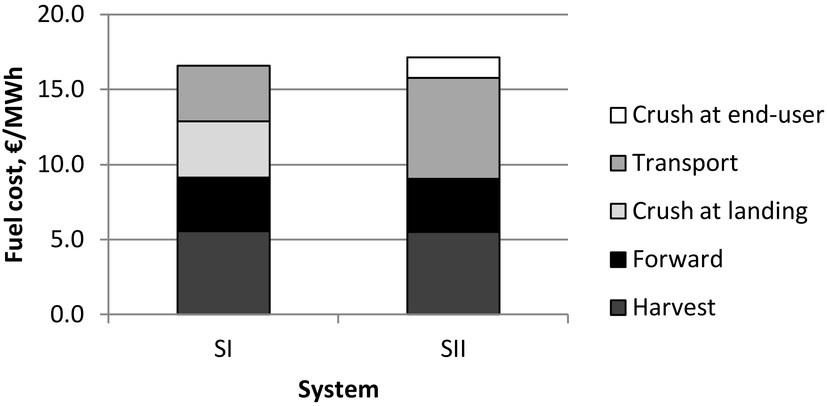

Figure 8. Contribution of different activities to final delivery cost for the base case in Paper I.

To assess the importance of the study factors for the fuel cost, each of the factors was varied, one at a time, from their base level to their high and low level. All factors except payload had an effect on cost (Figure 9). Small losses at the landing due to dry matter losses during storage and due to loading from the ground and missed material by the forwarder at the clear-cut area all influenced the final cost. Leaving stumps in the ground at the start made a minor impact.

The value of forest fuel products delivered is a function of both quantity and quality. In Paper I, the consequences of different storage outcomes were addressed. It was found that moisture content could reduce the cost of the delivered fuel, but also that poorly planned storage could drastically increase the cost. Ash content also proved to be an important quality parameter strongly connected to cost, given the simulated changes (Figure 9).

Tested variations in machine performance caused large changes in the system outcome. A decrease in productivity for the stump harvester, the forwarder and the mobile crusher in system SI had detrimental effects, whereas improvements had smaller effects. The cost response to changes related to the truck was more evident in system SII due to its inferior transport capacity, which resulted in more round trips given the same amount of fuel to transport. The variations in transport distance tested had, as expected, an important impact on the cost. Site size was also strongly connected to cost and for this factor a reduction was more important than an increase, and more evident for system SI (Figure 9).

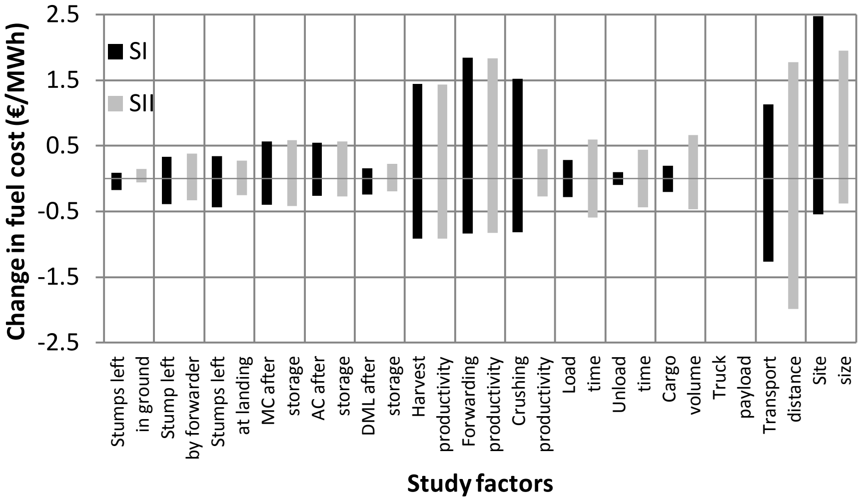

Figure 9. Effects on fuel cost (€/MWh) of individually changing one factor at a time in system SI (black) and SII (grey) in Paper I from its zero level to its low and high level. MC = moisture content, AC = ash content, DML = dry matter losses.

All activities that involve machine relocation, *e.g.* harvesting, forwarding and landing comminution, suffer from working with small objects. A general pattern that emerged was that system SI was preferable when the transport distance was long and the object size was large (Figure 10). System SII, on the other hand, was better for small objects and short distances. The breakpoint between the two systems was between 10 and 70 km, with the exact point determined by object size.

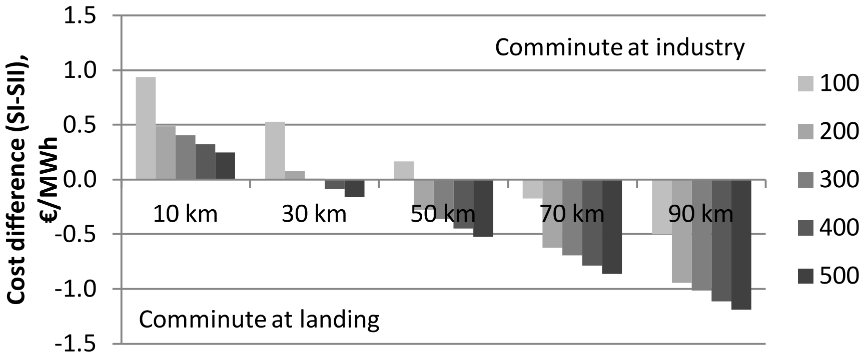

Figure 10. Cost difference between system SI, with transport before comminution (Comminute at industry), and system SII, with comminution before transport (Comminute at landing), with increasing stump harvesting site size (100–500 oven-dry tonnes odt) and increasing transport distance to the end-user (10-90 km). A zero value indicates equally large fuel costs.

6.2 Selecting appropriate machine systems

Selecting appropriate machine systems involves finding suitable systems for each set of objects, *e.g.* in a situation with some common transport distance. When operating a hot system, it also deals with questions such as balancing the system and planning the right transport capacity for a given comminution output.

In Paper II, the cost varied considerably in an overall comparison between all systems and configurations (Figure 11). The hot systems showed larger variations than the cold systems, which were more predictable. The large variation was explained by systems having different proportions of machines in unutilised mode, *e.g.* in queues or waiting for other units. For the hot systems, excess truck capacity helped hold down the cost for an idle crusher. An unbalanced system with too much truck capacity would lead to the crusher becoming the bottleneck in the system, thus restricting the output and leading to similar cost levels irrespective of distance (Figure 11). None of the configurations (number of trucks used) had a perfect balance between spare capacity of both truck and crusher for all distances studied. One truck was never the best alternative for the hot systems, while adding a second chip truck almost doubled crusher utilisation (Figure 12). The system using one hook-lift truck and containers resulted in lower costs than that using only one chip truck, due to the buffering capacity the three extra containers offered, which helped keeping the crusher busy, especially for short distances (Figure 12). Depending on distance, the aim should be to have two or three trucks working with the crusher. From the simulation results, a cost transition point for different configurations could be identified. The chip truck system (S2) had its transition point between two and three trucks at around 60 km, whereas for the hook-lift truck system (S3) it was at around 90 km.

In an overall comparison, the self-loading alternative transporting crushed material provided the lowest costs. However, for longer distances, 125-150 km, three hook-lift trucks and containers resulted in similar costs. For short distances, comminution after transport was a good alternative. However, the cost of that system increased more sharply than for other systems with increased distance, although still not resulting in as high costs as the hot systems using only one truck.

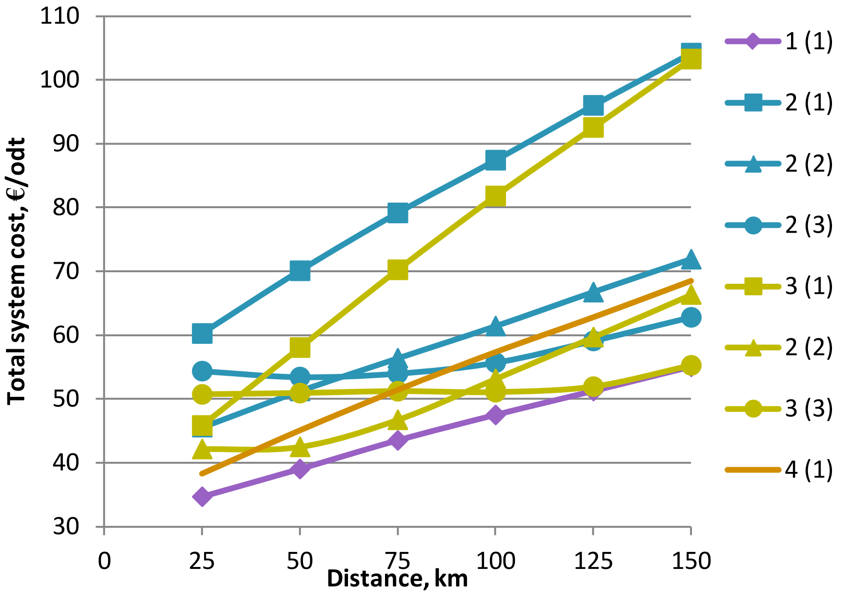

Figure 11. Total system cost for transport and comminution of stump wood as a function of transport distance for each of the systems (S1-S4) evaluated in Paper II.

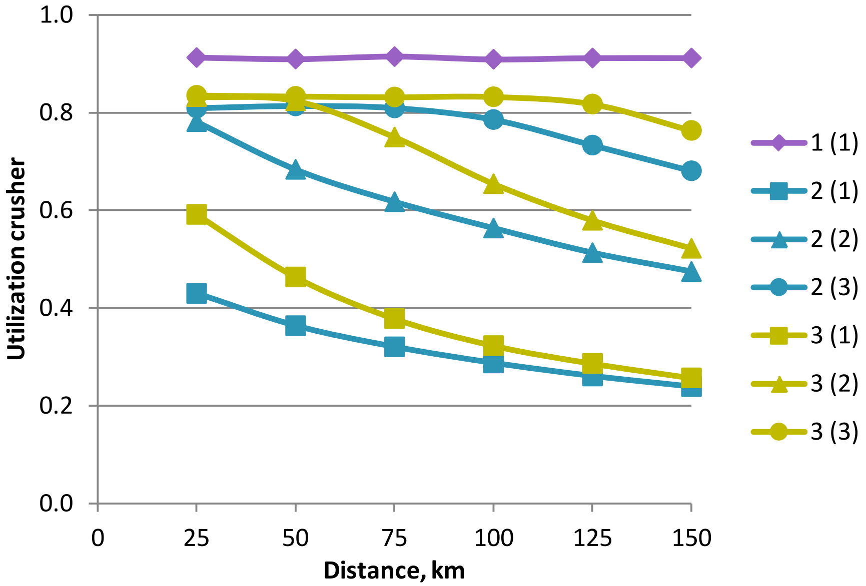

Figure 12. Crusher utilisation as a function of transport distance for the systems based on mobile comminution at the forest landing evaluated in Paper II (S1-S3). For explanation of system codes, see Figure 4. The number in brackets for each system is number of trucks.

6.3 Change in work organisation

The amount of forest fuel that can be delivered given a set of machines depends on the quality of the material and the specifications of the machines, *e.g.* cargo space. However, it also depends on how the machines work. Work organisation affects the output of the system, which can mean more material given a set of resources and higher utilisation rates for specific machines.

The machine concept studied in Paper III comprised a hot system with possible waiting times for each of the three machine types included; *trucks*, *chipper* and *forwarder* for container shunting.

The greatest number of loads delivered was achieved when operating with four trucks on a staggered schedule and with six containers in the buffer. Up to a distance of 70 km, chipper productivity was the bottleneck, while thereafter truck capacity was the limiting factor. In general, increased number of containers in the buffer and a staggered schedule resulted in more loads delivered. Both of those changes in system design also affected the cost of each load delivered. For short distances, the cost was reduced more by adding three extra containers than by adding one extra truck. Changing the scheduling principle proved even more preferable for short distances. For longer distances, the effects of more trucks were more visible. A staggered schedule was preferable when more trucks were operating (Figure 13).

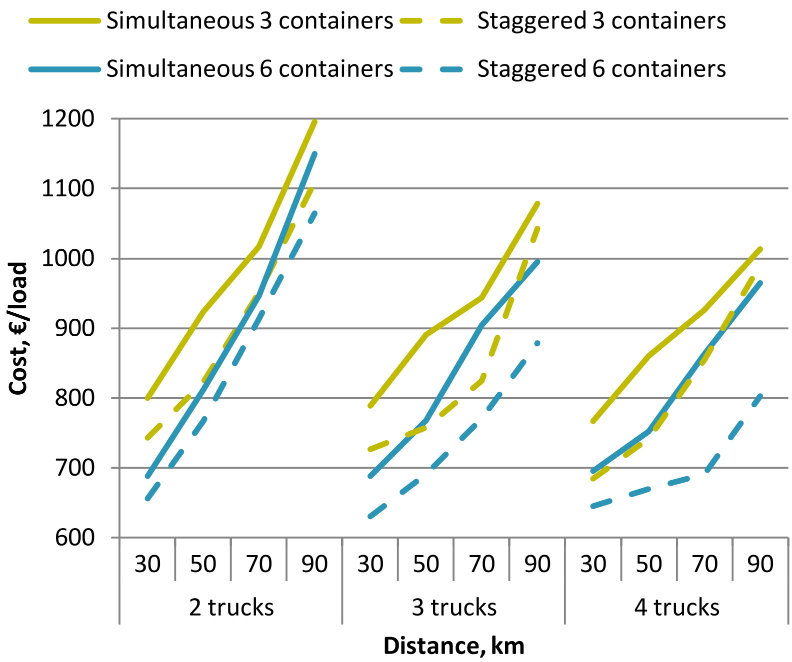

Figure 13. Total cost per load for the two different scheduling principles (simultaneous (full line) or staggered (dashed line)) and two different buffer sizes (three or six containers) evaluated for two, three and four trucks at different road transport distances in Paper III.

On separating system costs into cost components, it was found that all three work tasks were affected by the transport distance (Figure 14). Two container trucks gave the lowest transport costs at most distances, due to short waiting times at the landings and an overall low unused proportion of the scheduled time. On the other hand, it gave the highest costs for the chipping and shunting operations, as it created a lot of waiting time for both the chipper and the forwarder. In every case, the lowest costs for these two operations were obtained by using four container trucks, as this gave the lowest proportion of waiting time for the chipper.

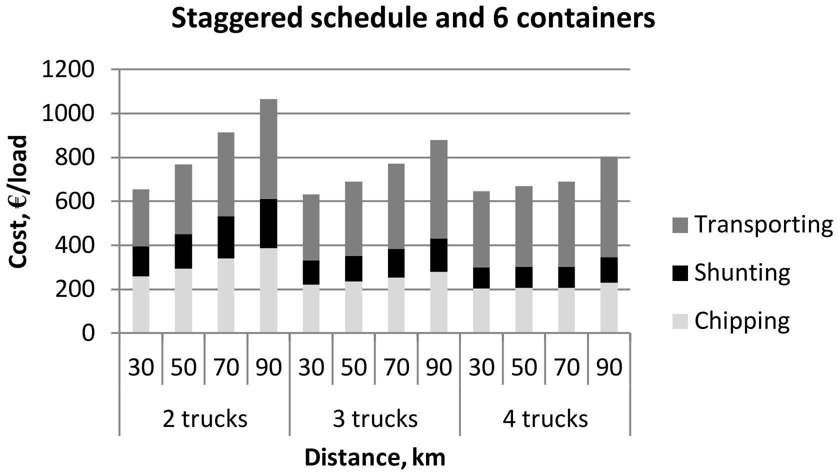

Figure 14. Cost components for two, three and four truck options operating on a staggered schedule and with six extra containers (Paper III).

6.4 Smart resource allocation to cope with varied fuel demand

Besides working with different systems using different forms of work organisation, it is also possible to actively choose where to work. Paper I indicated that storage outcome was important for system costs. Considering an industry with a varied demand for chips and with a limited on-site storage capacity as in Paper IV, it was challenging for the supply system when material was expected to be delivered directly from the forest. During the simulations, all objects were affected by the same set of weather conditions. In the simulation experiment, the difference between the strategies evaluated was how they prioritised which object to work with. This clearly resulted in large qualitative differences in the delivered material, especially with respect to moisture content profile (Figure 15). The Random strategy delivered the driest material when little energy was required and that with the highest moisture content when more energy was needed. There were no monthly differences in moisture content in the delivered material compared with the average moisture content of all stored material for that strategy. The other three strategies did the opposite, delivering a drier material compared with the average of all stored windrows by using different prioritisation strategies for which object to deliver when. The Fast Track strategy delivered material during summer that was stored for a short period of time, while in winter seasoned material stored for longer times was available for delivery. The Quality strategy sought to achieve a certain quality profile by prioritising biomass from certain regions and material stored for specific periods, which resulted in more high quality material in the winter. The Location strategy delivered material from more distant areas during summer, which when delivering according to first in-first out (FIFO) during winter resulted in transport distance being shorter compared with the average for all. However, the average delivered moisture content during the whole simulation period was similar: 44.5%, 44.3%, 44.0 and 44.1 for the Random, Fast Track, Quality and Location strategies, respectively.

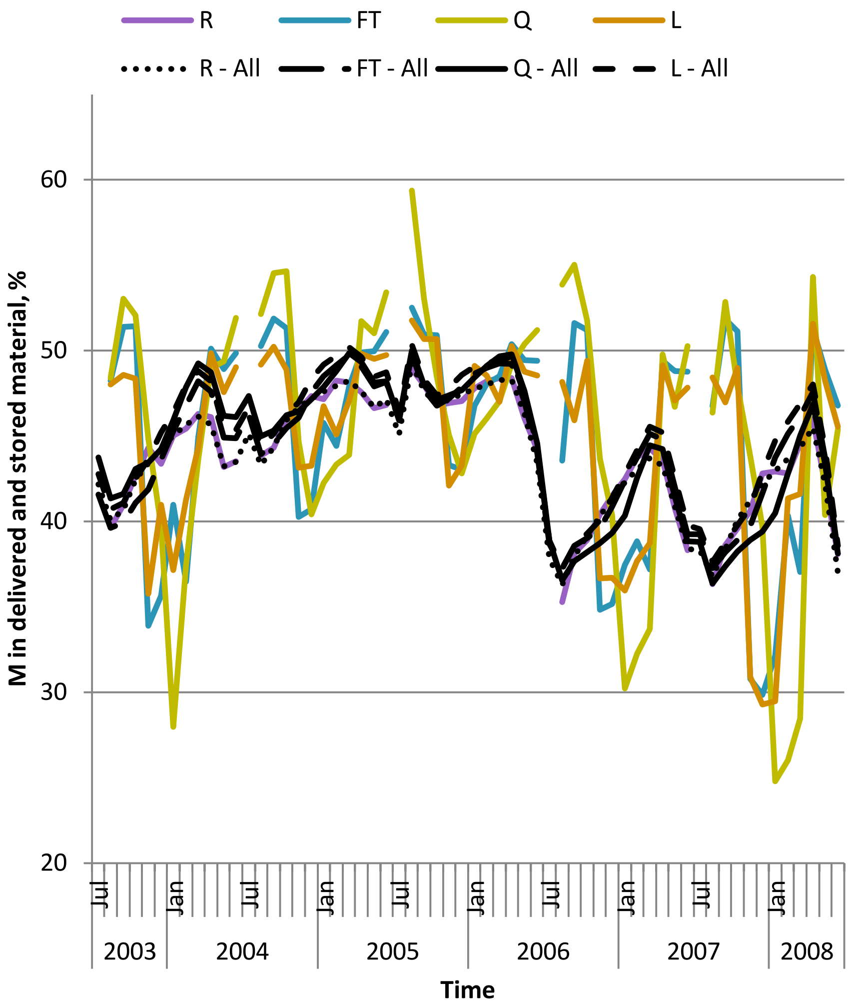

Figure 15. Monthly average moisture content (M) in the delivered material and average M in all stored windrows for each strategy evaluated in Paper IV (R = Random, FT = Fast Track, Q = Quality, L = location).

Moreover, the supply system as such was also heavily affected by the strategy used. For each of the four scenarios, the number of turns per month was determined by: 1) The site from where the material was transported and 2) the quality of each object handled. Comparing the strategies, only small differences were seen in total number of turns. However, the Random strategy required the most number of turns using trucks in a demand-driven line (Table 1). When information was added to help make informed decisions, fewer extra turns were needed and the other three strategies were all significantly better in that regard (Table 1). In addition, for the random strategy fewer turns were possible with an ordinary truck line, since it was more often unable to deliver material due to a full inventory at the industry. In total, the Quality strategy was best, as it required 21% less turns with the extra truck line compared with the Random strategy using no information (Table 1). Additional advantages were a more homogeneous material with less variation in moisture content.

Table 1. *Total number of truck turns for an ordinary truck line and an extra demand-driven truck line for each strategy evaluated in Paper IV (R = Random, FT = Fast Track, Q = Quality, L = Location)*

Number of truck turns	Strategy			
	R	FT	Q	L
Ordinary truck line	13 639	14 204	14 324	13 983
Extra demand-driven truck line	4 228	3 524	3 333	3 673

7 Discussion

7.1 Application of the results

The work described in this thesis had a Swedish focus, but specific results can also be applied to countries similar to Sweden and the more general findings have an even wider range of application. Moreover, the methodology and the models developed can be generalised and used in other areas with new resources, end-users and boundary conditions. They can also be tailored towards other specific situations, such as a case study (Eriksson *et al.*, 2015).

Sweden is a large country and local conditions vary between regions, *e.g.* regarding transport distance and biomass per object. However, in some of the studies described in this thesis these factors were handled as experimental factors. When interpreting results, a real case can be placed somewhere in a matrix of experimental factors. Some simulations were conducted in idealised cases regarding *e.g.* transport distances and fuel quality. By understanding the systems in those cases, it was then possible to transfer results and apply them to actual operations.

Moreover, the studies performed provided information on system behaviour, general trends and patterns, rather than precise figures applicable to each and every situation.

Stump fuel and logging residues were considered in the thesis but, although these are two different assortments, the supply chain activities within these systems are similar (Routa *et al.*, 2012) and some results can provide valuable insights for both types of material. The discussion below handles both types of material interchangeably.

Although the models and the simulations were designed to have a heating plant or combined heating and power plant as the end-user, the results in this thesis could also be used when planning supply and procurement of forest biomass to other end-destinations, *e.g.* biorefineries, thermal treatment plants and industries producing liquid biofuels, pyrolysis oil or bio-methane. Establishing infrastructure for forest biomass supply, at present intended for energy, can facilitate biomass reaching more high-value products in a future bioeconomy. The end-user was taken as an active component of the model only in Paper IV. In Papers I-III there was no direct effect for the rest of the supply system, as they only considered the end-user as a delivery point. Similar systems to those analysed in this thesis can be used to deliver material to other end-users with different preferences in terms of quality and delivery time. These new end-users may need a more steady supply with less demand fluctuations, which would help forest fuel handling contractors in their long-term planning and investment decisions.

In Paper IV, a novel methodology for the forest fuel area, in which historical weather data drive the end-user demand and control the quality changes on a daily basis, was developed. This approach can be applied in other similar problem areas, if sufficient system input data are available. The model can also serve other purposes besides studying machine allocation problems.

7.2 Increasing efficiency in forest fuel supply chains

Forest fuel supply chain efficiency can be improved in several different ways and in several different areas. The results presented below should not be interpreted as being the only ways to achieve higher efficiency in these systems. Other alternatives not covered in the thesis might be possible.

When implementing a new system, such as for stump wood, it is important to recognise that good management of logistic activities is vital for success. Many new systems fail due to poor planning of logistics (Ballou, 1992). For forest fuel, the logistic cost is the largest cost component (Brunberg, 2013). The most important message from this thesis relating to cutting costs is that in a given situation, it is more important to avoid working with the least cost-efficient systems than to strive to work with the best. It is evident that for hot systems, operating with only one truck is never efficient and the inefficiency increases with distance. None of the configurations had a perfect balance between spare capacity of truck and crusher, regardless of distance. It can thus be concluded that there is no such thing as a perfect system, but each system can have its own niche where it can use its strengths in the best possible way.

For hot systems, system balance strongly affected the system costs, meaning that active resource planning, including both comminution and transport resources given the prevailing operating conditions, is important. It is critical to have high utilisation of the comminution unit, since it is more costly than the transport units. However, maintaining high utilisation in these systems is challenging (Aman *et al.*, 2011; Asikainen, 2010; Spinelli & Visser, 2009). Extra containers at the landing helped decouple the transport and comminution operation, leading to a less hot system due to the added buffering capacity. To facilitate comminution, investing in more containers compared with more trucks can be strategically sound, considering the investment cost associated with those two alternatives in relation to the added value. Using a six container buffer might be difficult at some locations, especially if the landing is small and forest roads are narrow.

The cost transition point between different systems can be valuable as guidance, but will vary due to the local conditions. Crusher productivity will affect this point and a high productivity system, as in Paper III, will have a different transition point than a low productivity system, as in Paper II.

In order to cut costs, it is also important to minimise idle and queue time in the system. Besides through balancing truck and comminution capacity, this can also be done by scheduling the trucks so that all do not start simultaneously every morning. Using variable starting times always proved to be a good alternative in this thesis, but for two truck options the difference between a fixed and a variable schedule was less pronounced. This might be one reason why many contractors still work with fixed starting times, even when using more trucks. The findings in this thesis compensate for this lack of knowledge and can facilitate sound operational decisions.

The results presented in this thesis also show that the work organisation at landings can be re-arranged by using a shunting unit to keep a highly productive chipper more active. Earlier studies have also highlighted that the work organisation at landings and different methods for container handling can increase the utilisation of the comminution unit (Eriksson *et al.*, 2014b).

It is well known in supply chain management that trying to optimise individual functions and activities may come with the expense of increased cost for the supply chain as a whole. By recognising that the system can be more than the sum of its individual parts, more efficient structures can be designed (Christopher, 2005). For forest fuel systems this is relevant since several different actors form the supply chain. It is thus easy to end up with a sub-optimal solution if two different contractors are responsible for transport and comminution, which is a common situation in practice. Both are rational and try to optimise their own business, but for the whole system this does not lead to an optimal outcome.

A cold system will have less unnecessary waiting times and self-loading systems are more predictable, which is valuable when planning. Comminution at landing and delivering with a self-loading truck were always a good alternative in the present analysis, irrespective of conditions. As stated by Hall *et al.* (2001), the simplest supply system is often the cheapest.

There are many players involved in the forest fuel supply chain; the end-user, the supply/procurement company, one or two contractors responsible for transport and comminution and one or two more for harvesting and forwarding. The forest owner is another stakeholder to consider. Simulation models are a good way of creating a more holistic system overview, thus helping in developing better systems and aiding in decision making. For example, even if it is known when *e.g.* forwarding should be done with respect to quality, the material may nevertheless be handled at other times for practical and economic reasons. One machine might be nearby and provide other benefits to the system than quality-related considerations. An endeavour to achieve faster regeneration can affect the time for forwarding, even if this altered time is not preferable from a fuel quality perspective.

Performance of machines in the supply chain strongly affects the delivery costs. The performance, when active not idle, can vary considerably due to *e.g.* local conditions. Planning and finding suitable harvesting areas and allocating machines to these will keep costs down. The operator is an important factor affecting productivity (Sirén & Aaltio, 2003), which also calls for proper training. This makes it important for operators to work with the same tasks for some time, to gain experience and reach a stable productivity level, which for small businesses such as stump wood harvesting could be difficult.

To reduce inactive time in the supply chain, it is important to avoid objects that are too small, especially if many machines need to be relocated and re-established at a new location, since interactions can cause delays. This is a more important factor for stump fuel systems, since these involve more large machines than logging residue systems that have many functions integrated in the same unit. Much can be gained by just avoiding the smallest objects, while searching for the largest objects is of lesser importance.

Every time material is handled, time and resources are invested in the process and handling costs are added (Hall *et al.*, 2001). The fuel cost is obtained by comparing input (cost of processes) with output (value of delivered fuel). All losses affect the amount of fuel delivered, but losses at a later stage in the supply chain affect more processes than losses at an earlier stage, and therefore contribute more to the fuel cost, as more money has been invested in the lost fuel. A stump that is not harvested has minor negative effects on the fuel cost, since no machine time is invested in it. Lost stump fuel at landing means that the work done by contractors responsible for upstream processes has been in vain.

Asikainen (2015) discussed a shift in mindset in forest engineering from the conventional way of reducing inputs (cost) to instead an aim of value creation in the supply chain. This thesis confirmed the importance of considering value in the supply chain and working with quality to cut costs. Changes in fuel quality can be achieved passively, without input of resources and effort, only by *e.g.* smart planning of storage. If the forwarder could spend some extra minutes finding a more wind- and sun-exposed location for storage, this would pay dividends later due to a better storage outcome. Longer storage times can increase quality, but increased capital costs and potential dry matter losses must be considered. There is no guarantee of achieving natural drying, as the material can be rewetted in rainy periods. Large monetary losses arise if the material is delivered at untimely periods due to the trading system based on lower heating value, which is mainly a function of moisture content. It is also possible to achieve quality improvements actively by adding machines that *e.g.* sieve the material. A buyer wants to know that delivered fuel fulfils quality requirements and some heating plants are still reluctant to buy stump fuel due to bad experiences, mainly due to contaminated material with high ash content. Sieving can be a way to achieve a more homogeneous fuel with less fine fraction, lower ash content and an assured quality. However, both the sieving operation and material sieved out as reject add to the costs (Eriksson *et al.*, 2015; Eriksson *et al.*, 2014a).

There is a willingness in any organisation to shorten lead times. All actors want fast cash flow and low inventory of stocks, as a large inventory increases the financial burden by limiting the working capital (Christopher, 2005). Besides, a long lead time makes it more difficult to respond to quick changes in *e.g.* the market. Forest fuel supply chains today are characterised by long lead times, while at the same time the demand at the end-user varies widely in the short term, fluctuates with season and has a total yearly energy demand that varies between years. This sets challenges for the supply companies and involved contactors. In such case, supply companies must be agile and listen to the market, and try to predict future needs, and contractors requires an overcapacity of logistics resources to handle peak load periods (Svanberg, 2016). A supply system, where forest fuels are pushed into the system instead of being contracted by the users, can be problematic in a fluctuating market. On the other hand, a pull-orientated approach with a need that creates upstream actions can also be problematic due to the often required storage times. A general trend in supply chain management is quick response logistics where information systems, helps to provide the right product in the right place at the right time (Christopher, 2005). For forest fuel supply chains, a case where a planner has full overview of storage locations, amount at each location and current quality would be valuable. However, the physical, chemical and biological processes that drive quality changes make an exact overview impossible (Lehtikangas, 1999; Jirjis, 1995).

There are two aspects to the quality issue for forest fuels, especially with moisture content being used to determine product value. On the one hand, the contractors are paid more when delivering drier material and thus strive to reduce the moisture content by activities within the supply chain before delivering the fuel. Achieving this can open up areas previously not sufficiently profitable for forest fuel collection, *e.g.* too distant areas, thereby resulting in more forest fuel reaching the market. On the other hand, the heating plants are designed for a specific moisture content and today many of the larger plants are equipped with efficient flue gas condensation that can recover 'free' energy from moist fuels (Ericsson & Werner, 2016). New product categorisations and specifications for forest fuels are proposed to facilitate more fair business agreements (Fridh *et al.*, 2015).

In Paper IV in this thesis, improvements were achieved in yearly machine utilisation for the units working with transport and comminution by adding information and prioritising objects actively. A chipper often has difficulties finding work in low-load seasons, whereas other units such as a container truck it might be easier finding other work tasks outside the heating season. In Paper IV, it was assumed that the chipper trucks were used for both chipping and transporting the material. The efficiency of such a system can be debated, since it can be considered non-efficient to transport a heavy chipper back and forth between the forest and the end-user, reducing both possible weight and volume that could otherwise have been used for transporting chips. On the other hand, since this is a cold system it solves the problem of idle time due to machine interactions. A contractor just needs one person for the two operations, although a chipper truck can work together with other transport units.

The forest fuel supply chain is not an isolated business and it is tightly connected to conventional logging operations. Residues are a by-product of logging and the harvestable potential is therefore a result of the extent of logging. Integration of conventional logging operations and forest fuel operations was not addressed in this thesis, but earlier studies have shown benefits, *e.g.* using one combi-forwarder instead of two single-purpose machines (von Hofsten & Eliasson, 2016).

This thesis considered only direct transport of fuel from the forest to the end-user. However, a terminal provides many advantages, *e.g.* the possibility to change to more efficient transport modes (ships and trains), provide delivery security and level out unbalanced supply-demand situations throughout the season, offer advantages of scale related to comminution and possibilities to increase value, and improve and tailor quality towards specific requirements by mixing fuels. Yearly machine utilisation for comminution units could be improved through storage terminal. However, a terminal is also costly to establish and run, adds extra handling and results in longer total transport distance (Virkkunen *et al.*, 2016; Virkkunen *et al.*, 2015; Rauch & Gronalt, 2010; Kanzian *et al.*, 2009; Eriksson & Björheden, 1989). Moreover, a large amount of biomass is stored at terminals, which poses greater risks of storage-related problems. This risk increases further if the biomass is comminuted (Lehtikangas, 1999; Jirjis, 1995).

Today, heating plants have to rely heavily on the supply company and its ability to deliver with high precision. A trend is that many heating companies want to take control over the supply chain by vertical integration, *e.g.* by running a receiving terminal near the plant (Svanberg, 2016).

7.3 Methodological discussion

In line with the definition of a model, the simulation models developed here were a simplification of the reality. However, based on the verification and validation tests described in section 5.6 of this thesis, they seem accurate enough for their intended purpose. Simulation models contain two types of uncertainty: data uncertainty and model uncertainty (Anon, 2007a). The results presented in this thesis are a function of both the input data used and the models developed with their specific model logic, and are thus affected by both types of uncertainties.

The fact that stump fuel systems are not yet widely established in practice and not thoroughly studied makes some form of uncertainty inevitable, especially data uncertainty are expected. On the other hand, 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, enabling good estimates of process characteristics to be produced through input modelling (Biller, 2010). If more data were available, distribution fitting software included in the simulation package could be used for the real dataset, creating more realistic distributions. One weakness in the input data was that a detailed dataset for breakdown and repair times was not available. Approximations from other studies and the characteristics of the process, together with approximations on average expected outcomes, were used to develop proper input models. 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. In this work 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, based on assumed hourly usage. This might result in an overestimate of the cost of idle machine time. A distant-dependent empirical equation for average truck driving speed was 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 can be assumed to be valid for all transport activities.

Regarding model uncertainty, one drawback with the models developed is that they are robust with respect to the machine operators included, which are non-flexible and only do what the model states. In reality machine operators are more flexible, and have some room for creativity that the models lack. A real operator can take their own decisions, good or bad. On the other hand, different scenarios or strategies are easier to compare when the human factor is excluded, as in the models. Weather delays, which in reality can have a large effect on the supply system, 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 part of the route. In timber procurement, backhauling has been shown to have potential for efficiency improvements (Palander & Väätäinen, 2005). Furthermore, only situations where truck(s) work together with one comminution unit were considered here, and in actual operations a truck can be redirected to other crushers to efficiently utilize the transport capacity. The specifications of machines can vary significantly between different types, which affects the results. If another type/model of a machine with other specifications were assumed, different results might be obtained.

8 Conclusions

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

- It is important to select suitable sites for forest fuel harvesting and to use an appropriate machine system for the site. Proper planning can help reduce supply cost
- There is no such thing as a perfect system and each system can have its own niche
- To achieve high efficiency for hot systems, transport and comminution must be seen as one operation, not two separate operations. A proper balance in machine capacity is needed
- Introducing extra containers as a buffer for comminuted material helps decouple transport and comminution, thus making the system less hot
- Minimising idle time is key to cost-efficient transport and comminution systems. Smart planning and scheduling of resources can reduce unnecessary idle time in the system
- A cold self-loading system is always a viable alternative. However for long distances, comminution before transport is required
- Fuel quality is strongly linked to the supply system, which ideally should be planned with respect to present quality
- It is possible to tailor fuel deliveries concerning quality by delivering the right biomass at the right time
- By actively prioritising biomass storage, improvements that level out some of the yearly production and demand imbalances can be achieved.

9 Suggested further research

Future study areas include investigating the fuel costs for different delivery strategies, including costs for tied-up capital and losses for different storage regimes and the economic consequence of varied machine utilisation. There are indications that these costs are of large importance, even if in practice they are hard to measure and therefore account for. Creating a more lean supply chain and increasing the possibilities of shorter storage times are an interesting future focus area.

Further investigations of allocation principles for resources and development of simple guidelines, rules of thumb or good principles concerning allocation given available information are important future research areas. Technical systems for quality monitoring that could be incorporated into a company's decisions systems are also desirable.

Although terminals add cost, the benefits for the system of using more terminals are an important research area. Quality changes in large-scale storage of wood chips between seasons also require more detailed study.

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