Dissertationes Forestales 146

Operational efficiency of forest energy supply chains in different operational environments

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Academic dissertation

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ABSTRACT

Ambitious international efforts to combat climate change have lead to a large interest about the use of forest biomass for energy in many countries. In order to meet the expected growing demand in the future, it will be necessary to improve operational efficiency of existing forest energy supply chains and support the establishment of efficient supply chains in new operational environments.

The thesis applied a three-dimensional approach which examines forest energy supply chains from a technical, social and economic viewpoint. Four case studies in different operational environments have been carried out to investigate the applicability of the three dimensional approach to improve operational efficiency. The technical dimension was investigated in Paper I and II. In Paper I, the effects of climatic conditions, covering of piles, and partial debarking on drying of roundwood were studied in four experimental trials located in Scotland, Finland and Italy. In Paper II, the chipping of forest biomass was studied in two different operational environments. The investigation of the social dimension in Paper III provides insights into the setup of two different supply chains through business process mapping and simulation. Finally, in paper IV, which investigated the economic dimension, an analysis of the effect of the operational environment on technology selection and design of supply chains, is presented.

The thesis demonstrates that the chosen approach was practical to investigate the complex relationships between the chosen technologies and different supply chain actors and stakeholders thereby contributing to maintain or improve operational efficiency of forest energy supply chains. Due to its applicability in different operational environments, the approach is also suitable in a more global context. Furthermore, it captures the effect of different aspects and characteristics of the various operational environments on the setup and organization of supply chains. This will be valuable knowledge to ensure or improve operational efficiency when adapting existing forest energy supply chains or when building up supply chains in new operational environments. The benefit to consider the different dimensions is that it allows gaining a broader understanding of the challenges at different stages of forest energy supply and how they relate to each other. Furthermore, the analysis of the case studies in the context of the three-dimensional approach also revealed that timing and planning of the different operations and processes is essential to improve or maintain operational efficiency.

Keywords: biomass, wood-fuel logistics, forest machinery, bioenergy supply

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Joensuu, May 2012
Dominik Röser

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers, which are referred to in the text by their Roman numerals I–IV. The articles I, II and IV are reprinted with the kind permission of the publishers while the study III is the author version of the submitted manuscript.

I Röser, D., Mola-Yudego, B., Sikanen, L., Prinz, R., Gritten, D., Emer, B., Väätäinen, K. & Erkkilä, A. 2011. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. Biomass and Bioenergy. 35(10):4238–(42)47. doi:10.1016/j.biombioe.2011.07.011

II Röser, D., Mola-Yudego, B., Prinz, R., Emer, B. & Sikanen, L. 2012. Chipping operations and efficiency in different operational environments. Silva Fennica 46(2): 275–286. http://www.metla.fi/silvafennica/full/sf462275.pdf

III Windisch, J., Röser, D., Mola-Yudego, B., Sikanen, L. & Asikainen, A. 2012. Business process mapping and simulation of a Finnish and a German forest biomass supply chain. Manuscript.

IV Röser, D., Sikanen, L., Asikainen, A., Parikka, H. & Väätäinen, K. 2011. Productivity and cost of mechanized energy wood harvesting in Northern Scotland. Biomass and Bioenergy. 35(11):4570–(45)80. doi:10.1016/j.biombioe.2011.06.028

Dominik Röser had the main responsibility in regard to the entire work done in Papers I, II and IV. Beatrice Emer and Robert Prinz, helped in the collection of data, Heikki Parikka helped with the GIS analysis. Co-authors in their respective papers helped with the discussion of the ideas, set up of the experiments and analysis of the results. Finally, in paper III, the author and Johannes Windisch shared responsibility for the design of the study, method selection, data analysis, interpretation of the results and writing of the article. Johannes Windisch was responsible, in addition, for the data collection and calculations. Papers I, II and IV are reprinted with kind permission of the journals concerned.

CONTENTS

1 INTRODUCTION

1.1 Background

Policy developments supporting the use of forest biomass for energy
The IEA World Energy Outlook (IEA 2011) gives a sense of urgency regarding recent developments in the energy markets and global efforts to combat climate change. In the report it is stated that under its "New Policies Scenario, which assumes that recent government commitments are implemented in a cautious manner, world primary demand for energy will increase by one-third between 2010 and 2035 and energy-related CO_2 emissions will increase by 20%." These figures underline the future challenges to produce energy for the ever-increasing population of our planet. In the future it will be a great challenge to maintain the current standard of living, on a sustainable basis, which is why European policy makers have implemented ambitious efforts to combat climate change and support energy self-sufficiency by promoting the use of competitive, secure, and environmental friendly renewable energy sources (CEC 2002). In the IEA World Energy Outlook (IEA 2011), the importance of renewable energy sources is recognized by stating that "even though it comes with a high price, renewable energy sources will bring long-term benefits in terms of energy security and environmental protection".

Today's efforts to increase the shares of renewable energy are based on a mixture of different renewable energy sources. The importance of bioenergy to achieve these ambitious targets was already realized in 1996 by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's report stated that bioenergy is considered the most important energy source of the future. Already in 1997 the European Commission took the first step towards a more environmental friendly energy system with the White Paper for a Community Strategy and Action Plan COM (97) 599 (CEC 1997). The target was to increase the share of renewable energy sources of the EU's total energy consumption to 12% by the year 2010. In 2008, the EU published the so-called 20/20/20 targets, which called for a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels, 20% of EU energy consumption to come from renewable resources and a 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency (European Commission 2008). Under Article 4 of the European Renewable Energy Directive (2009/28/EC) (EU 2009) each Member State was to submit a plan (National Renewable Action Plan) describing how this target is to be achieved by the year 2020. The use of forest biomass for energy plays an important role in achieving these national targets. In 2010, according to Mantau et al. (2010), the total consumption of wood resources for energy production in the EU 27 was approximately 346 million cubic meters which roughly translates into 73 Mtoe. The importance of forests is demonstrated by the fact that of the total supply of the one billion cubic of all woody resources in the EU 27, approximately 70% were derived from forests and 30% from woody biomass originating from outside the forest (Mantau et al. 2010). It is expected that forests will continue to play a major role in the production of renewable bioenergy, particularly in light of the ambitious 20/20/20 targets. Furthermore, recent national developments, such as Germany's decision to terminate the use of nuclear energy, can be expected to increase the demand for forest biomass for energy even further (Bundesrat 2011). Wood should form a significant contribution to reach these targets (Verkerk et al. 2011). In fact, wood and wood waste account for approximately 50% of the total renewable energy production (Eurostat 2011). Furthermore, there is a large potential to increase the use of forest resources, as fellings are currently below the annual increment in many European countries. Their utilization could be increased considerably while maintaining accepted sustainability criteria (MCPFE 2007). However, a study released by Mantau et al. (2010) argues that depending on the utilization scenarios presented in the study, there might not be enough raw materials available to meet the growing demand for renewable energy and the growing competition between material and energetic use of wood. Additionally, ecological concerns, such as nutrient depletion or loss of biodiversity, might also limit the amount of available resources (Stupak et al. 2008).

Sources of forest biomass for energy

When managed on a sustainable basis, trees growing in forests form an abundant, local and environmental friendly source of fuel. In addition, the use of forest biomass for energy contributes to rural development, energy independence, income, and employment in rural areas (Lunnan et al. 2008, Röser et al. 2008). The ambitious policy developments combined with other associated benefits has lead to a large increase in the use of forest biomass for energy in many European countries (Röser et al. 2008).

There are many different types of wood based fuels (Figure 1). Primary residues are obtained directly from the forest operations, whereas secondary residues are obtained as by-products of the industrial processes associated to forest products. Other sources of wood-based fuels include traditional firewood and tertiary residues, which consist mainly of recycled wood. Finally, energy forests, which include fast growing tree species in very short rotations, are another source of energy and their contribution to the total energy balance is expected to increase in the future (Mola-Yudego 2010).

At present, the largest share of energy from wood comes from secondary residues of the traditional forest industries, namely, the pulp and paper and sawmilling industries. However, forest industries across Europe have been facing difficulties in light of the recent global recession with reduced demand for pulp and paper and the resulting reduction in production capacity. This has lead to a decrease in the use of wood for energy due to a lack of by-products, such as black liquor, bark, and sawdust. In this context, the use of residues from thinning operations, in particular, represent a great potential source of raw material to increase the use of forest biomass for energy, independent of the large industrial processes.

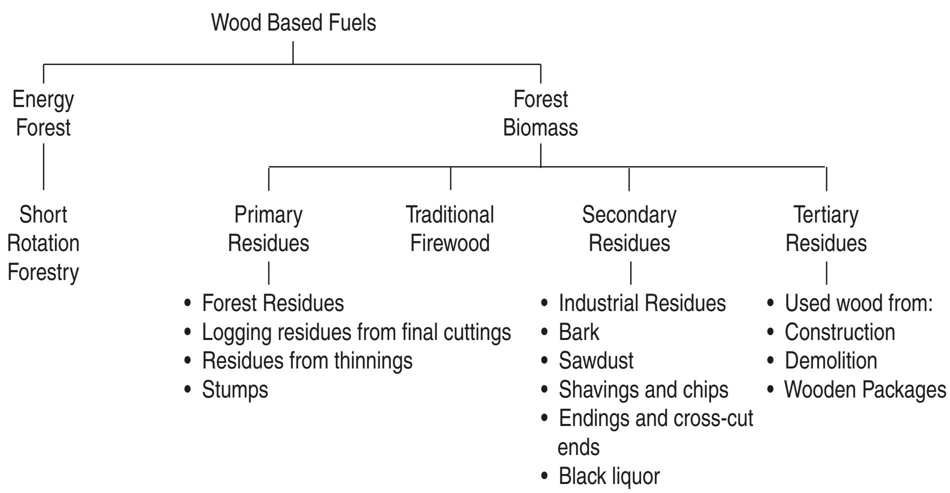


Figure 1. Classification of wood based fuels (Röser et al. 2008).

Primary residues consist of logging residues from final cuttings, residues from first and intermediate thinning, and stumps. Today, the most commonly used form of primary forest biomass for energy is the logging residues which are a by-product of traditional roundwood harvesting processes (Asikainen et al. 2008). A survey of European supply chain systems carried out by Diaz-Yànez (2010) revealed that logging residues represent 52% of the sources of forest chips, whereas thinning residues accounted for about 23%. Since logging residues are a by-product of traditional harvesting operations, they are available with limited extra harvesting costs, which makes them an attractive source of energy. In Finland, and to a small extent, Sweden and the UK, stumps from final felling operations of mainly spruce (*Picea abies*) have been another attractive by-product of traditional roundwood harvesting operations. However, due to the fact that stumps are only utilized in large-scale combined heat and power plants (CHP) and because of ecological concerns (Repo et al. 2011), it is not expected that the utilization of stumps will find a European wide application. Thinning residues, on the other hand, pose a great potential to increase the share of forest biomass for energy in the future (Asikainen et al. 2008, Nordfjell and Iwarsson Wide 2011). In 2009, the raw material coming from thinning operations had already surpassed logging residues in Finland (Ylitalo 2010). So far, the challenge of raw material from thinnings has been the associated high harvesting costs (Laitila et al. 2010a). Still, it can be expected that raw materials from thinnings will play an important role to meet the targets set by the EU and their utilization will increase significantly once their production becomes more economically feasible.

Development of forest biomass for energy in the past decade

The development of forest biomass in Finland and Sweden, the most progressive countries when it comes to the use of forest biomass for energy in Europe, has a long tradition (Routa 2012). The utilization of forest biomass for energy varied considerably in the last three decades mostly due to the fluctuation of fossil fuel prices (Hakkila 2006, Björheden 2011, Routa et al. 2012). Development in these countries was promoted by vast amounts of available forest resources and insignificant deposits of fossil fuels. Moreover, there has been constant public support to develop the use of forest biomass for industrial and energy purposes in both countries. This has lead to a situation where the use of forest biomass for energy has been based on the large-scale utilization of both primary and secondary residues (Figure 1). In Sweden, approximately one third and in Finland approximately one fifth of the energy used is originating from forest biomass (Thorsén et al. 2011, Ylitalo 2011). Today, Finland and Sweden still rely, largely, on the large-scale use of forest biomass, and, during the last decade the use of forest biomass for energy has seen a rapid increase with the installation of a large number of community heating plants and combined heat and power plants (Ylitalo 2011). At present, the number of heating plants using wood biomass in Finland is approximately 800 (Ylitalo 2011). While the largest development to increase the share of renewable energy sources in the last decade was in the installation of community scale heating plants in Finland, it is expected that in the next few years the focus of the development will be on converting the existing larger CHP plants from fossil fuels to wood biomass (Laitila et al. 2010b).

The large-scale plants that have, historically, been the backbone of forest biomass for energy in Finland and Sweden are lacking in most other European countries. Before the ambitious climate change targets set by the EU, the interest in forest biomass for energy for heat and electricity production was only marginal, and limited to traditional chopped firewood. This was also due to the availability of other cheap fossil fuels, such as coal, in many European countries. Moreover, in the past decade, EU policies to combat climate change and an increasing desire to become more energy independent, have bolstered the case of renewable energy sources and consequently the use of forest biomass for energy. As a result, the development in the utilization of forest biomass for energy has been similar to Sweden and Finland in regards to the establishment of numerous smaller scale district heating networks in many other European countries (Ylitalo 2011, Landwirtschaftskammer Österreich 2011, BBE 2012, Clara 2006). These district heating networks provide heat and/ or electricity for municipal buildings, apartment blocks, and private homes. Moreover, the use of traditional firewood has been a significant source of forest biomass for energy in many European countries. In Finland, for example, the use of forest chips exceeded the use of traditional firewood for the first time in 2010 (Ylitalo 2011).

The use of forest biomass is distinct when compared to other sources of energy, such as heating oil or gas, due to the complex make-up of supply chains and varying raw material demands of different utilization places (Asikainen et al. 2002). Many heating plant operators are used to dealing with oil and gas where national and international supply structures are already in place and logistics solutions are already established. However, when dealing with the use of forest biomass for energy, the situation is very different since there are diverse forms and qualities of raw material, more complex and less developed supply structures, as well as varying demands on the final quality of the product by different customers. Therefore, the development of efficient and robust supply structures is a demanding task when establishing new energy systems based on forest biomass. Consequently, there can be shortages of local expertise in the development of reliable supply structures in countries without any prior experience regarding the production of forest biomass for energy. There are cases where the establishment of the supply structures or heating plants has failed due to the lack of technology, know-how and knowledge about the supply systems and available resources.

When smaller plants were established in Finland and Sweden, it was possible to partly overcome these challenges by relying on existing expertise in the mechanized harvesting of roundwood. Moreover, it was possible to integrate forest fuel and traditional roundwood harvesting operations, which is considered to be one of the key factors to success (Andersson et al. 2002). This development resulted in the uptake of existing and proven technology and a very high rate of mechanization in these operations (Hakkila 2004). However, the development did not come without challenges and problems even in Finland and Sweden, which had to be overcome along the way. Large amounts were invested into the research, development, and education about these systems (Hakkila 2004, 2006, Björheden 2011, Routa et al. 2012).

When developing small scale supply chains for forest biomass for energy, other European countries could not rely on abundant existing expertise as the know-how and expertise regarding the procurement of forest biomass for energy was not as developed as in Finland and Sweden. Furthermore, due to the establishment of mostly smaller scale heating plants, the fuel quality requirements were posing extra challenges for fuel procurement. Consequently, the development of forest fuel supply structures in many European countries was not as mechanized and focused on smaller scale entrepreneurs and supply chains when compared to Finland and Sweden (Kühmeier et al. 2007, Asikainen et al. 2008, Eberhardinger et al. 2009, Eberhardinger 2010,).

Forest energy supply chains

In this thesis, the concept of *forest energy supply chains* refers to the sequence of operations that are conventionally performed in order to procure the raw material (forest biomass) from the source to the end user (energy production). Over the course of the last decade, similar supply structures and chains for logging and thinning residues have developed in most European countries as the production of forest biomass follows a logical process from the forest to the heating/CHP plant. During this process, the following steps have to be considered, each of them dependent on the available forest resources described in Figure 1 (Andersson et al. 2002). These include the collection of the forest biomass according to demand and quality requirements, preparation of this biomass according to quality requirements and for efficient transportation and finally the transport of the biomass to the heating/CHP plant including storage.

In the case of logging residues, the collection of forest biomass is comparatively simple since the biomass is already "harvested" during the roundwood harvesting. Several studies have been carried out on the productivity of logging residue harvesting which includes the pre-piling and forwarding of the logging residues from the stand to the roadside landing (Asikainen et al. 2001, Nurmi 2007). The pre-concentration and pre-piling of the logging residues, already during the harvesting of roundwood, is essential to ensure an efficient forwarding of the raw material (Hakkila 2004).

In the case of thinning residues, a separate harvesting operation has to be carried out, which is followed by the harvesting of the biomass. A lot of the technological and method development in recent years, particularly in Finland and Sweden, has focused on improving the efficiency of harvesting in first and intermediate thinnings (Spinelli et al. 2007a/b, Eberhardinger 2010, Laitila et al. 2010a, Belbo 2011).

The chipping operation is considered an essential step in the supply chain since it is affected by a large number of outside factors, such as raw material, equipment used, and the organization of the work (Hakkila 2004, Eberhardinger 2007, 2010). There are several options to achieve the preparation of the biomass. One method that integrates the collection and preparation of forest biomass into one operation is in-woods chipping, in which the biomass is harvested and chipped by the same machine. However, this system is only applied, on a larger scale, in a limited number of countries (Eberhardinger 2010, Asikainen et al. 2008) since the overall costs tend to be higher compared to other harvesting systems. In addition to this, in-woods chipping is limited by environmental conditions such as slope or uneven terrain (Hakkila 2004, Kühmeier et al. 2007, Rottensteiner and Stampfer 2009). Other options to prepare the biomass are chipping either at roadside, at a terminal, or at the end use facility. Each system comes with its own benefits and drawbacks, and various studies have been carried out to find the most suitable place for the comminuting of biomass in different operational environments (e.g. Ranta 2002).

Another essential aspect of the preparation phase is the proper storage and drying of biomass in order to improve fuel quality and reduce transportation costs (Ranta 2002, Asikainen et al. 2002, Eberhardinger 2010).

The most critical and challenging phase of biomass supply chains is the transportation (Asikainen et al. 2002, Ranta 2002, Hakkila 2004). Consequently, most of the available supply chains have developed aiming at solving the transportation problem. The main challenge for transportation is based on two variables, namely, the low energy density per volume and the moisture content of the fuel (Hakkila 2004, Asikainen et al. 2002). In order to increase the efficiency of transportation, it is necessary to find ways to improve fuel density and reduce moisture content prior to the transportation of forest biomass. Many different methods, technologies, and supply chains have been tested and developed to address the three main factors of collection, preparation, and transportation of forest biomass. However, there are often challenges to implement them in practice (Andersson et al. 2002, Kanzian 2005, Eberhardinger 2010, Kühmeier et al. 2007). Over the years, the practice in many countries has demonstrated that the chipping at roadside with subsequent transportation to the heating plant is a reliable, universal and cost efficient method for the production of forest biomass for energy (Wittkopf 2005, Cremer 2009, Asikainen et al. 2011b). This was confirmed in a recent survey carried out by Diaz-Yànez (2010). The survey demonstrated that the technology and supply chain to produce forest chips from logging and thinning residues with the widest uptake across Europe is the chipping of raw material at roadside. The reasons why chipping at roadside has been so successful are multifold. Primarily, the advantage is the enhanced transport economy due to higher payload of the transport vehicle. Moreover, chipping at roadside allows for the delivery of chips to different customers and enables limited storage capacity at the plant. Furthermore, the chipping at roadside system relies on proven and reliable technology which, in return, is limiting the amount of downtime of the machines (Routa et al. 2012). The chipping at roadside is carried out using a wide variety of mobile chippers. They range from farm tractor based chippers in smaller scale operations to large-scale chippers for industrial production of forest chips. In most parts of Europe, small to medium sized chippers are used, whereas, the use of large-scale chippers is mostly limited to Finland and Sweden for the production of industrial chips for large-scale district heating networks. An illustration of a commonly used supply chain based on chipping at roadside is presented in Figure 2. Usually, the chips are blown directly into the load space of the truck or container, which transports the chips from the roadside landing to the heating/CHP plant (Ranta 2002, Eberhardinger 2010, Cremer 2009). Chipping at roadside is considered a "hot" supply chain (Ranta 2002), because the chipper can only work if a truck is on site. This is causing additional demands on the logistics. As a result, in the Alp region, or in Sweden, it is common to initially blow chips on the ground and then load them again with a truck that is equipped with a loader (Kanzian et al. 2009, Eliasson 2011b). Furthermore, the use of chipper-trucks, where a truck is equipped with a chipper and a small load space for the chips, has been gaining popularity in Sweden as it eliminates waiting times between machines (Eliasson 2011a).

The complexity of forest biomass supply chains, due to the large number of decisions, as well as inter- and intra- organizational concerns, was discussed by Weintraub and Epstein (2002) and remains a future challenge for the development of forest energy supply chains. When operating CHP and heating plants based on biomass, the quality of the fuel is a key factor for success or failure of the systems. Fuel quality is usually determined by the fuel handling system and the combustion technology applied at the production facility (Ranta 2002). In general, fuel quality requirements are decreasing with increasing plant size. In return, this means that relatively small heating plants as they are commonly used in many countries in the EU, have relatively high demands on the fuel quality. The higher quality demands, which are mainly characterized by low moisture, ash content and an even particle

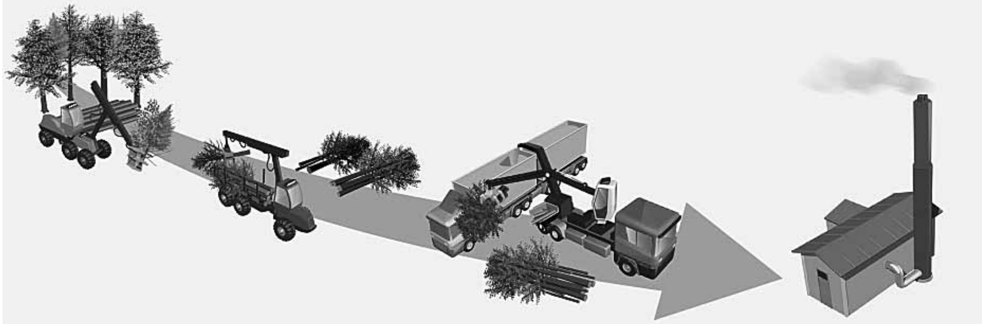


Figure 2. Common supply chain based on chipping at roadside in Finland.

size distribution, are associated with higher harvesting costs (Stupak et al. 2008). The efficient production of forest biomass for energy is therefore causing additional challenges where the expertise in the production of high quality fuel chips is limited or completely lacking. The seasonal variations of demand of forest biomass and weather patterns are additional factors adding to the complexity of forest biomass supply systems (Andersson et al. 2002). Whereas the highest demand for forest biomass is during the winter month, the production of forest biomass varies seasonally. The situation is further complicated by the fact that heat loads of heating plants are very low during the summer month (Andersson et al. 2002). Moreover, the biomass has to be stored for at least one or two drying seasons, which is further adding to the complicated seasonal variations in regards to logistics and weather. According to Ranta (2002), the logistics are an essential part of forest biomass supply and further developments should focus on the different phases of forest biomass procurement along the supply chain. The large number of involved stakeholders in forest biomass supply is yet another aspect adding to the large complexity of forest biomass supply. The number of stakeholders is challenging from two different viewpoints. On the one hand, all stakeholders in the supply chain have to make a profit within their share of the supply chain, and on the other hand, they are all interlinked and dependent on each other. Quality of the end product might also be affected as what happens early in the supply stage might have large impact later in the supply chain. This forms a complicated net in which all interests based on a social and economic nature have to be satisfied. Finally, the decentralized nature of energy systems based on forest biomass, combined with the varying forest biomass resources, results in a complex framework in which the cost structure of forest biomass supply may vary. This can be an issue even between different projects (Roos and Rakos 2000), which is a great challenge for making long term wide ranging plans for the utilization of forest biomass for energy.

1.2 Research gaps

A study by Asikainen (2011b) revealed the large number of investments into technology and training of manpower needed to meet the targets set by the EU. The study is addressing the key challenges ahead, which include the available technology, manpower and consequently also efficient supply chains to produce forest biomass for energy. By increasing the efficiency of forest machines through technological developments and better educated machine operators, it will be possible to reduce the overall machine needs and manpower. However, the cost level and consequent efficiency of supply chains is, according to Stupak et al. (2008), dependent on six factors which are: 1) Accessibility of the stand. 2) Density and volumes of fuel (in piles, on site and on a regional level). 3) Forwarding and transportation distances. 4) Fuel quality. 5) Factors related to storage and buffers. 6) Applied harvesting method and technology. Stand accessibility, densities, volumes, and forwarding and transportation distances are variables that cannot be directly influenced by the harvesting method since they are dependent on the operational environment. Fuel quality, storage, and the applied harvesting methods and technologies are, on the other hand, factors that can be affected by the various stakeholders along the supply chains. In recent years, studies have been carried out to examine and improve each independent variable in a given operational environment (e.g. Webster 2006, Nurmi 2007, Laitila et al. 2010).

However, fuel quality, storage and the applied harvesting methods and technologies are dependent of each other and there are close interlinkages (e.g. fuel quality is affected by the storage methods and used harvesting technology). In order to investigate shortcomings and optimize existing supply chains, taking into account the different operational environments, it is necessary to take a comprehensive approach where the whole supply chain and system is considered and analyzed from a technical, organizational and economic viewpoint. In each country, supply chains have developed differently, and each development has come with its own set of advantages and drawbacks. Therefore, knowledge about different operational environments is beneficial to generate new and innovative knowledge about supply chains for forest energy. In addition, this knowledge also allows bridging the gap between countries with extensive knowledge and know-how, and countries that lack this particular knowledge. The benefits for both countries are significant since it provides business opportunities and knowledge building for the provider countries, and minimizes the growing pains in recipient countries.

1.3 Operational environment

There are various definitions for “Operational environment” depending on the discipline and sector involved. However, they all share a very similar approach. For example, Mason and Langenheim (1957) describe operational environment in ecology as phenomena that are immediately and directly operationally significant. The Department of Defense (2010) defines operational environment as a “composite of the conditions, circumstances, and influences that affect the employment of military forces and bear on the decisions of the unit commander” in the Dictionary of Military and Associated Terms. Wheelen and Hunger (1995) describe the operational environment as a combination of internal variables and external variables within an organization that are usually not within the short term control of management. In forest science, this approach was applied by Kurttila et al. (2001) to describe the attitude of Finnish forest owners towards the operational environment of forestry. What all these definitions have in common is that they describe certain circumstances potentially affecting something that is operating. Certain aspects of all the above mentioned definitions are relevant to the operational environment as it is understood in this thesis. The operational environment describes more than just the working environment in which people or a system work. It also includes the internal and external factors that have an effect on everyday operations of e.g. a forest energy harvesting entrepreneur as was described by Wheelen and Hunger (1995). These include the political and policy framework, the working culture in a certain region, the cultural background, ecological considerations, exposure to forest harvesting technology and know-how as well as climatic conditions. The concept of operational environment as applied in this thesis is presented in Figure 3.

1.4 General framework for the thesis

According to Blanchard and Fabrycky (1981) a system can be defined as “an assemblage or combination of elements or parts forming a complex or unitary whole”. When dealing with forest energy supply we are dealing with a system in which several parts (actors) are working together to form a larger unit to achieve a common objective. As this thesis examines an approach that assists in the improvement of existing as well as in the establishment of new forest energy supply chains it is touching on two engineering approaches namely systems engineering which is “bringing systems into being” and systems analysis that deals with “improving systems already in being” (Blanchard and Fabrycky 1981). The chosen approach has also similarities to methods engineering as defined by Groover (2007) which has the overall objective to increase productivity and efficiency. The common denominator of all

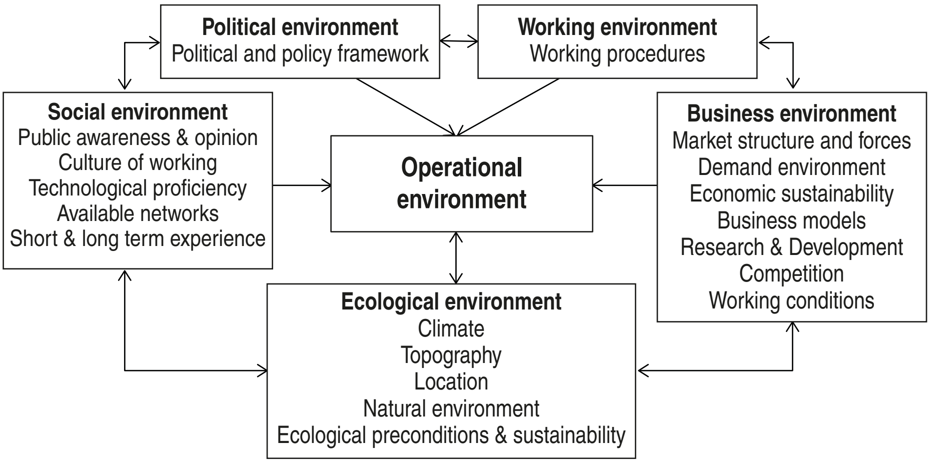


Figure 3. The concept of operational environment in the forest biomass for energy business.

these approaches and this thesis is to look at the system as a whole and to investigate how a system can either be established or how an existing system can be improved.

This has also been the aim of research in forest operations, which has a long history starting with the industrial revolution which caused a shortage of forest workers, and consequently the need to increase productivity of forest operations (Sundberg 1988, Samset 1992, Heinimann 1995, Björheden 2010). Heinimann (2007) described forest operations as a scientific discipline that addresses "design, implementation, control, and continuous improvement of forest operations systems". From a scientific viewpoint, forest operations research is a challenging field since, by its nature, it is an applied scientific discipline which demands knowledge about the principles of several other scientific disciplines (Harstela 1993, Björheden 2010, Uusitalo 2010). This is also reflected in the work presented in this thesis.

According to Harstela (1993), work science is a division of scientific knowledge that deals with "work itself, productivity and quality of work, its impacts in society and forest ecosystems, man at work, machines, tools, and other capital inputs as well as methods and techniques of work". The work presented in this thesis is utilizing methods introduced by Harstela (1993), in order to improve the operational efficiency of supply chains for forest energy. However, this raises the question on what is operational efficiency.

According to Pfeiffer (1967), operational efficiency can be defined as "the effectiveness with which human potential and capital are utilized in a production system". Similarly, in their description of the problem of operational efficiency in forestry, Sundberg and Silversides (1988) state that the "choice of the right technology" to meet different challenges is "a problem requiring knowledge and skill to be correctly solved. Once these overarching challenges have been solved, other problems related to e.g. planning, implementation and execution of the operations become apparent".

Sunderberg and Silversides (1988) further summarize these challenges as: "The problem to allocate in space and time labour and machines, to put them to work in a rational fashion and to maintain or improve their efficiency" and group problems in three categories of a **technical, social** and **economic** nature. Consequently, by considering each of these dimensions and how they are connected the operational efficiency of forest energy supply chains can be improved.

As a result, this thesis is applying and examining a holistic three-dimensional approach to investigate how operational efficiency of forest energy supply chains can be improved in different operational environments. The three-dimensional approach is examined by carrying out four case studies, which are complemented with a review of existing literature in order to observe forest fuel supply chains in different operational environments from a technical, social and economic perspective (Figure 4).

The **technical dimension** is related to the different materials, tools, and machines that are necessary to harvest, process, and transport the biomass from the forest to the end-use facility. Furthermore, it includes the processes of selecting, preserving, and enhancing the technical means to execute the job (Sundberg and Silversides 1988). At the technical level, separate processes in the supply chain can be analyzed and improved individually in order to improve the whole supply chain. Two case studies have been performed to investigate operational efficiency and means to improve it at the process level in different operational environments. In paper I, the effects of climatic conditions, covering of piles, and partial debarking on drying of roundwood are studied in four experimental trials located in Scotland, Finland and Italy to examine drying times of typical raw material for forest energy (Paper I). The chipping of forest biomass is studied in two different operational environments (Germany and Finland) in Paper II. The study is performed to identify the chipping productivity under varying conditions. The study explores the effects of various machine set-ups and differences in the working environment. Furthermore, existing literature is used to complement and discuss the findings from Papers I and II.

The **social dimension**, according to Sundberg and Silversides (1988), includes issues related to work safety, health issues, human capital, and work satisfaction. The focus of the social issues in this thesis is adapted to focus on the people involved in the managing and operation of the supply chain and a wider comparison of the organizational setup of different forest fuel supply chains in varying environments. As supply chains in different regions have been established based on dissimilar operational environments (Hakkila 2004) the case study presented in Paper III is used to investigate and determine the effect of the operational environment, on the operational setup, and efficiency in different regions.

The aims under **economic dimension** as presented by Sunderberg and Silversides (1988) are to "balance the inputs of man, machines and other assets for performing the job so as to meet the objectives". The underlying objectives, despite the complex framework, are to carry out the work at the lowest possible cost. The economic dimension, as it is applied in this thesis, is essential as it encompasses both the technical and social dimensions. Without economic sustainability in the short and long term supply chains are not viable. Therefore, the economic dimension includes the feasibility of the system in the greater context. A case study is carried out in Paper IV that demonstrates how this objective can be achieved. The case study in Scotland investigates how the production of forest biomass for energy can be economically sustainable in the short and long term and how technology selection and design of supply chains in Scotland can affect the overall operational efficiency.

Sunderberg and Silversides (1988) provide a "shopping list" of what we need to know to solve challenges associated with operational efficiency. They include: "Which are the technical means for doing the job, what can labor perform equipped with these means, which factors have influence on the performance, and how, what are the cost of the inputs, what are the prices on the outputs, what restrictions are present in doing the job". These items are used as the starting point to investigate how operational efficiency of supply chains for forest energy can be improved in different operational environments.

The terms efficiency, effectiveness and productivity are often used without any clear separation of their meanings. In scientific literature, however, there is a clear distinction between their definitions and goals. Heinimann (2001), for example, notes that understanding productivity is an important factor when aiming to improve the operational efficiency of harvesting systems. In order to clarify the differences between productivity, efficiency and effectiveness they can be defined as follows. Productivity is defined by Groover (2007) as "the level of output of a given process relative to the level of input". Whereas efficiency is described as "the ratio of standard performance time to actual performance time" by Karger and Bayha (1977) which means that efficiency is usually described as a percentage. Effectiveness on the other hand is not measureable but rather refers to the capacity to produce an anticipated output (Drucker 2006). A more descriptive definition of efficiency vs. effectiveness was given by Ahn and Dyckhoff (1997). In their characterization of efficiency and effectiveness, efficiency was described as "do[ing] the right things right" and effectiveness as "do[ing] the right things".

Assisting in determining the right things is the work introduced by Pfeiffer (1967) (Figure 4). Pfeiffer (1967) states that operational efficiency can be increased by adapting the methods of operation, using various dissimilar material and equipment, educating the labor force, improving the work place (working environment) through better environmental conditions and working climate, the standardization of working methods, and the integration of operations. Finally, the holistic viewpoint is of importance since it offers an overreaching perspective to the whole system in comparison to just looking at a single operation in one operational environment.

Figure 4 illustrates how the three-dimensional approach has been applied in this thesis. As not all factors potentially affecting operational efficiency were covered in the presented case

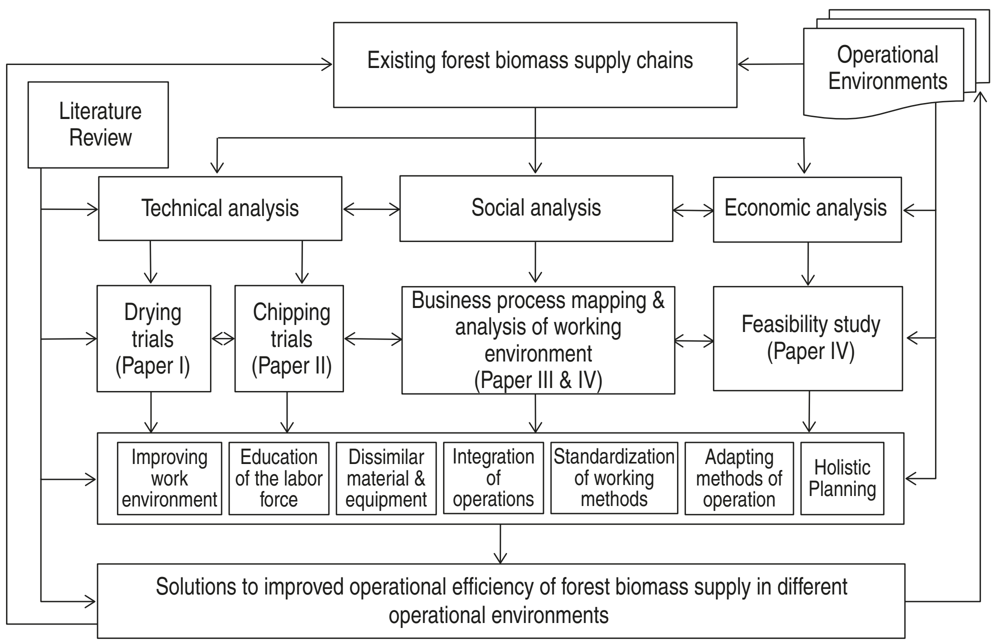


Figure 4. General framework for the thesis.

studies, existing literature was used to bridge the gap between the results from papers I–IV and additional factors affecting operational efficiency. Finally, the literature review provides the opportunity to put the results of the case studies into context with existing literature.

1.5 Aims of the study

The thesis aims to investigate and improve operational efficiency of forest biomass supply chains in different operational environments by examining a three dimensional approach in which forest energy supply chains are investigated from a technical, social and economic perspective. Consequently more specific aims of the study are:

Technical dimension:

- To analyze the effect of natural drying in different European climatic conditions using partial debarking and covering to optimize fuel production and supply (Paper I).
- To study chipping operations in different operational environments and assess productivity and future improvements (Paper II)

Social dimension:

- To map and assess the organizational framework of forest fuel supply chains in different operational environments (Germany and Finland) (Paper II).

Economic dimension:

- To analyze the applicability, cost and feasibility of Nordic forest biomass supply chains in a different working environment in Scotland (Paper IV).

The results of this research will have applications in the uptake and improvement of forest energy supply chains and technologies in existing and new operational environments.

2 MATERIAL AND METHODS

In order to apply the three-dimensional approach in different operational environments case studies and experiments were carried out at 12 different locations in five European countries. The locations of the case studies and experiments are presented in Figure 5. The sites were chosen due to their characteristics in relation to the study objectives. However, in some instances the availability of local entrepreneurs and individuals to participate in or take care of the trial operations was the decisive factor for specific sites.

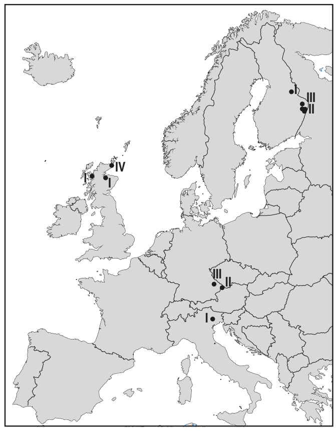


Figure 5. Location of different case studies in Papers I-IV.

2.1 Technical dimension

2.1.1 Effect of covering and debarking on moisture content (Paper I)

In order to investigate the technical dimension two separate studies were carried out (Paper I and II). Paper I investigated how fuel quality can be improved by setting up drying trials of biomass in different operational environments. In total, four study sites were chosen. Two of the trial sites were located in Scotland, one trial was established in Italy and one in Finland. In Finland the trials were located in Sotkamo, in the Eastern part of Finland. Finland was chosen to represent Nordic climatic conditions and due to the fact that it is currently one of the countries with the highest utilization of forest biomass for energy in Europe. Forest energy operations in Finland were considered to be more advanced among the different trial sites and typical Finnish practices were transferred to the cases in Scotland and Italy to test their applicability. Scotland was chosen as a study country due to the higher rainfall levels in comparison to the other study sites in Finland and Italy and to study whether the higher rainfall levels affect the rate of drying. In Scotland, the drying trials were established at two different locations. The first location was at the Glenlivet estate in Central Scotland. The second trial site was located on the Isle of Skye in the North-Western part of Scotland. Furthermore, the two sites in Scotland were chosen due to the increasing demand for forest biomass in the area. In Italy, the trials were located in Cappella Maggiore, in the Veneto region. Similar to Scotland, the site was mainly chosen due to its climatic conditions. It is representative of warmer climatic conditions in the mountainous regions where weather conditions are different from the Nordic countries and the UK. Furthermore, the entire Alp region has seen an increasing demand for forest biomass for energy in recent years and the development is expected to continue in the future. Another decisive factor in the selection of the trial sites was the use of similar harvesting operations and procedures in all countries.

The changes in moisture content of roundwood using various treatments were tested in four separate trials. The diameter at breast height (dbh) of the used roundwood ranged from about 5 to 32 cm with an average length of 3 to 4 m. All piles were placed on log bearers in a relatively open area along the forest roads to allow for natural drying through wind and sun. The number of piles and respective volumes are presented in Table 1.

Local weather conditions were collected from the weather stations closest to the respective study sites. In Paper I moisture content was measured using two different sampling methods. The first method, used in Cappella Maggiore, Sotkamo and Glenlivet, was based on changes in the overall weight of the pile. In Sotkamo and Glenlivet each pile was weighed in regular intervals using scales. In Cappella Maggiore, the tool used for the weighing was a load cell attached to the end of a crane. The second method, which was applied in all of the trials, was to take direct moisture samples at regular intervals from the upper, lower, lower and bottom parts of the piles. Sample discs with a thickness of approximately 2 to 3 cm were taken using a chainsaw. The samples were sealed in plastic bags and then analyzed in the laboratory to determine the dry weight of each sample. Additional information about the methods, e.g. debarking and covering are described in Röset et al. (2010). The percentage of the debarked area was determined based on analysis of digital photographs and the method introduced by Liiri et al. (2005).

In a first step, the resulting drying curves were assessed qualitatively by observing the changes in the moisture content of the piles. Subsequently, a mixed model approach was utilized to determine the overall effect of the treatments applied during the drying season. The interaction of the effects of species and location was applied as a grouping random factor. The model was fitted using restricted maximum likelihood. The dependent variable used was the relative moisture content referring to the first sample (when the wood was still fresh). For this analysis, at each location months were counted from the time that the piles were prepared, in order to include the different starting points of the drying season and to make the drying curves comparable. Given the non-linearity of the drying curves, the natural logarithm was applied to the relative moisture contents. The end of the drying season considered is presented in Table 2. However, in Capella Maggiore, all available records were incorporated. Ultimately, the effects of the treatments during the winter were analyzed as well by comparing the moisture values after the winter with their corresponding values at the end of the drying season.

Table 1. Trial setup in the different locations.

Location	No. of piles	Volume of piles (m^3 solid)
Cappella Maggiore (IT)	8	4-5
Sotkamo (FI)	6	5-6
Glenlivet (UK)	8	4-6
Skye (UK)	4	4-6

Table 2. End of drying season in different locations

Location	End of drying season (end of month)
Sotkamo (FI)	September
Glenlivet (UK)	October
Skye (UK)	November
Cappella Maggiore (IT)	–

2.1.2 Chipping of forest biomass (Paper II)

In order to have another common aspect of forest energy supply chains in the technical dimension Paper II was designed to investigate the effects on chipping productivity in two different operational environments. Five different sites were analyzed in Finland and one in Austria. The time studies in Finland were carried out in Tohmajärvi, Rääkylä, Pyhäselkä and Kitee. As in Paper I, Eastern Finland was chosen as a study site due to its long history in the production of forest biomass for energy and resulting high level of expertise in forest operations. The Austrian trial took place at Engelhartszell which the authors considered to be a representative forest biomass chipping operation for Central European conditions. The tree species used in all of the trials were representative of commonly used species for biomass for energy in Finland and Austria (see Table 3). The study was carried out at five different locations in Finland and at one location in Austria (Table 3). In all of the trials the chippers were operated by skilled operators and the chips were blown directly into the load space of the transportation vehicle which was serving as sample unit measure. The chipper was mounted with new knives at the start of each measurement day. In order to account for local practice an 80x80 mm sieve was used in Finland whereas a 35x35 sieve was used in Austria. However, one load in Austria was chipped using an 80x80 sieve and 3 loads in Finland were chipped using a 35x35 mm sieve to allow for a better comparison of the results.

In Finland, a total of 27 containers and in Austria a total of 17 containers were analyzed. Before chipping the dimension of all piles, percentages of species and average diameter of wood material to be chipped were measured and recorded. An overview of the used machines in each country is presented in Table 4.

A time study was carried out manually using the continuous time method (Harstela 1991) with Rufco hand-held data recorders. The time study was partly carried out in the field and partly by video analysis in the laboratory. Effective chipping time (E0) was documented and sub-divided according to crane movement elements and chipper feed orifice activities.

Table 3. Location of the tests, number of resulting containers, raw material assortments, sieve used and main species used.

Country	Location	Containers	Raw Material	Sieve (mm)	Main species
Finland	Kumpu	3	Whole trees	80x80	Alder (*Alnus incanca*)
		4	Whole trees	80x80	Birch (*Betula pendula/pubescens*) (30%) Pine (*Pinus sylvestris*) (70%)
		3	Whole trees	80x80	Birch (*Betula pendula/pubescens*) (80%)
	Rääkkylä	4	Whole trees	80x80	Birch (*Betula pendula/pubescens*) (40%) Aspen (*Populus tremula*) (40%)
		3	Logging residues		Spruce (*Picea abies*) (90%)
	Tohmajärvi	7	Stems	80x80	Pine (*Pinus sylvestris*)
	Kitee	3	Whole trees	35x35	Alder (*Alnus incanca*)
Austria	Engelhartszell	6	Whole trees	35x35	Spruce (*Pinus sylvestris*)
		10	Whole trees	35x35	Beech (*Fagus sylvatica*)
		1	Whole trees	80x80	Beech (*Fagus sylvatica*)

Furthermore, the number of crane loads was counted for each container to determine the size of the boom load. Time elements for the crane movements and chipper activities are presented in Table 5.

The analysis focused on the interaction of the chipper and the crane to study their performances and thus to limit idle times between them. There are various factors that might affect chipper or crane productivity. In the case of the chipper these are e.g. sieve size, sharpness of knives, tree species, diameter and moisture content of the raw material. Crane productivity, on the other hand, might be affected by the operator, raw material, storage set-up, diameter and local environmental conditions (e.g. slopes). As a result, production and idling are always inter-linked between the two units (Figure 6). The performance of the chipper has a direct effect on the waiting time of the crane, which has to wait for feeding when the chipper has insufficient capacity to process the wood.

The results were examined using the ANOVA tests to find significant differences amongst the various factors. A simple model was constructed for the analysis of the combined effect of location (i.e. country) and sieve on the productivity. The model was fitted using restricted maximum likelihood, and the variables were treated as dummy variables.

Table 4. Technology used for the trials in Finland and Austria

Location	Chipper	Crane	Tractor	Controls	Load space
Finland	Kesla C4560	KESLA 600T	Valtra S280, 250 HP	Tractor cabin	50 m^3 / Truck based
Austria	Kesla C4560	KESLA 600T	John Deere 7920, 300 HP	Tractor cabin	25 m^3/ Tractor based

Table 5. Time elements of the time study for crane movements and chipper feed orifice activities.

Crane movements	Chipper feed orifice activities
1. Boom out, grab and boom in	1. Feed orifice is full: chipping
2. Helping in feeding	2. Idling: waiting for material to be chipped
3. Waiting for feeding	
4. Other (e.g. moving material too big to be chipped)	

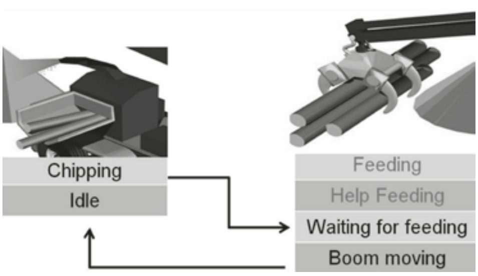


Figure 6. Description of the interrelationship between chipper and crane. The chipper element “Chipping” is directly related to the element “Waiting for feeding” of the crane: the crane cannot feed the chipper when it is already chipping. “Boom moving” directly affects the chipper: the chipper remains “idle” when the crane is moving material. The two other elements “Feeding” and “Help Feeding” can take place simultaneously to the chipper element “Chipping” and therefore do not directly affect the chipper productivity.

2.2 Social dimension

2.2.1 Business process mapping and simulation (Paper III)

In order to investigate the social dimension the organizational set up of typical supply chains in two different operational environments were investigated. The first supply chain was located in Eno in the Eastern part of Finland and the second in Feldkirchen-Westerham in Southern Germany. The supply chains were chosen based on the fact that both of them produce chips for district heating plants of comparable size in two different operational environments and due to the willingness of the supply chain stakeholders in both countries to participate in the study.

The supply chains investigated in Paper III are from Eno, Finland (ENO) and Feldkirchen-Westerham, Germany (FELD). The supply chain in ENO procures fuel for a 1.2 MW district heating plant whereas the chain in FELD provides fuel for a 1.5 MW district heating plant. Both plants are owned and managed by forest owner cooperatives.

The supply chain in ENO is managed by a local forest service company that focuses almost entirely on the procurement of roundwood and energywood. As a result, the company organizes and manages the entire procurement operation from wood harvesting to the delivery of the chips to the plant using local entrepreneurs. Another important player is the Forestry Centre (*Metsäkeskus*) that supports private forest owners and assists in finding stands from which forest fuel can be extracted. In ENO, precommercial thinnings represent the biggest source of forest biomass and average removals per logging site are approximately 90 m^3.

In FELD the local forest owners association (FOA), an affiliated company of the local cooperative, is one of the main suppliers of fuel to the plant. One major difference compared to Finland is that in Germany forest operations solely for energywood procurement from precommercial thinning are not common. As a result, the raw material basis for forest fuel is logging residues from integrated harvesting operations. The logging residues are procured by the FOA and sold to the cooperative which takes care of the chipping and transportation using local entrepreneurs. The average removal per logging site is typically 150 m^3.

The fact that in ENO, a custom made product (chips only) is procured, whereas in FELD the main source of fuel is a by-product constitutes a major difference. However, in this study no specific differentiation is made between the assortments.

The data for the business process mapping was gathered using expert interviews. The interviews included key personnel in the supply chains (Table 6). After the first round of interviews the maps were created using the Sigmaflow® software and then continuously evaluated, improved and verified together with the interviewees.

Table 6. Functional units of which the personal was interviewed during the data collection.

ENO	FELD
Forest Authority	Logging Contractor
Forest Service Company	FOA Operations Supervisor
Logging Contractor	FOA Accounting Office
Chipping Contractor	Chipping Contractor
	MWB Sales Manager
	MWB Logistics Manager

Basic techniques for business process mapping, as described by Damelio (1996), were used to initiate the data processing. During the course of the study a new process map design was developed that incorporated the flow sequence, communications and data exchanges between the functional units and payment processes. The software Sigmaflow® Mapper was used for creating the process maps. Table 7 defines the items used in the process maps.

The process sequence in a forest fuel supply chain is of large complexity and an event entering the supply chain does not always run through every single process in the map but follows a certain path depending on various decisions that occur during its processing. Therefore, to determine the work time expenditure for managerial and organizational tasks a discrete-event simulation model was chosen. After the development of the business process maps, the mean time consumption for every single process was estimated by experts from the Finnish Forest Research Institute.

Based on the process maps and the expert estimations of time consumption, models were built in order to determine the non-productive work load (NPWL). NPWL includes all processes except the ones that are related to the actual production, for instance logging, chipping, transportation, and delay times associated with the production. Depending on the particular situation different distribution were chosen for the simulation. Since in practice the time consumption of the different activities will vary over a wide range, the standard deviation

Table 7. Categorisation of objects used in the business process maps.

Type	Object	Description
Time consuming items	Payment	Transfer of money between functional units
	Communication	Exchange of data and paper documents by means of emails, phone calls, oral conversations, postings
	Activity	Activities are performed to fulfil sub tasks in the process such as creating maps, evaluating stands, moving between work sites etc.
Info items	Data	Any kind of information produced by an activity
	Paper document	Paper document produced by an activity such as forms, contracts etc. Can involve data produced earlier in the process
	Digital data storage	E.g. a database or Excel file
	Paper document storage	Data stored in form of paper documents
Others	Decisions	Decide the path the transaction takes through the process when different alternatives are given
	Start of process	Beginning of the process
	End of process	Endpoints of the process which can be successful or unsuccessful e.g. when the forest owner did not accept the conditions set by the forest service provider

was set to ±25% of the mean. The simulation was run 30 times using different random number streams. Per random number stream 30 to 35 transactions were simulated. The software used for the model building and running the simulation was SigmaFlow® Modeller. Due to limitations of the software it was necessary to build models for each functional unit separately which resulted in an overall number of 21 different models. In addition two extra models were built to further analyze the initial results, namely; the overall NPWL of ENO and FELD when the NPWL of the Forest Owner is left out of the simulation and the NPWL of the functional units in FELD that are in charge of managing and organizing the supply chain

2.3 Economic dimension

2.3.1 Productivity and feasibility calculations (Paper IV)

The investigation of the economic dimension is based on a case study in the northern part of Scotland, which was chosen due to the vastly available forest resources in the area and plans to construct a combined heat and power plant in the town of Wick. Initial discussions with local forest owners and other stakeholders combined with the existing knowledge in harvesting of traditional roundwood have lead to the realization of the potential to transfer some Nordic technologies and know-how to the Northern parts of Scotland.

All machine cost calculations presented in the study are based on investments in new machinery and equipment. The productivity models and functions are based on established Finnish supply chains. The data for the GIS analysis comprised 715 individual stand compartments. Altogether the forest area consisted of over 350 km^2. The mean size of a compartment or a forest in the calculations was about 50 ha. All timber in each stand was considered to be available for energy wood since, at the time of the study, there was no competition for the resource due to the remote location of the study area and a lack of local users. Furthermore, a road network theme layer Integrated Transport Network from the Ordnance Survey was used in combination with some manually added tracks. The Highland North Agreed Routes Map (Timber Transport Forum 2004) was used as a background map in GIS.

The different cost components of the supply chain such as cutting, forwarding and chipping were calculated based on experiences in Finland and modified for conditions in Northern Scotland (e.g. Table 8). Detailed transportation distance calculations and cost of transportation were calculated using GIS tools such as ArcGis and Finnish expertise (Högnas 2001, Laitila 2006, Sivonen 2006, Nurminen and Heinonen 2007).

The various considered options for processing the biomass are illustrated in Fig.7. The considered options were based on existing commonly used supply systems.

The most suitable harvesting and chipping method was determined by evaluating four different aspects of forest energy harvesting (Figure 22), namely; natural conditions, social considerations in relation to forest energy entrepreneurship and structure of supply, the limitations set by the combustion technology and their effects on the harvesting chain and the properties of the fuel itself.

Due to the unique situation in the northern part of Scotland, where, at the time of this study, a market for roundwood did not exist, it was considered that roundwood would be used for wood chips production. As a result, harvesting and forwarding costs of normal roundwood harvesting in Scotland were used in the calculations.

In the calculations, the chipping costs varied slightly depending on the location of chipping however a similar chipper was considered to operate at roadside, plant or terminal.

Table 8. Cost calculation details for chipping at roadside.

Price/Tractor/base machine	76765	€	Productivity		
Price/Chipper	145000	€	Small size wood (delimbed)	25	m^3 h-1
Price/Loader	40000	€	Pulpwood	35	m^3 h-1
Lifetime/Tractor	10	a	Whole tree (with branches)	20	m^3 h-1
Lifetime/Chipper	7	a	Annual work amount		
Lifetime/Loader	10	a	Small size wood (delimbed)	10000	m^3
Scrap value of tractor	15	%	Pulpwood	20000	m^3
Scrap value of chipper	20	%	Fixed costs		
Scrap value of loader	15	%	Total depreciation	26 496.5	€
Management and overheads	5800	€ a^{-1}	Interest	15 414.0	€
Insurances	2000	€ a^{-1}	Insurance	2 000.0	€
Risk	5	%	Management and overheads	5 800.0	€
Interest rate	5	%	Fixed costs total	49 710.4	€
Salary of the workers	18	€ h^{-1}	Variable costs		
Social expenses. %	60	%	Salaries	36 534.9	€
Price/Fuel	1.0	€ l^{-1}	Fuels and oils	45 257.1	€
Fuel consumption (chipping)	40.5	l h^{-1}	Maintenance	10 470.6	€
Fuel consumption (transfer)	30	l h^{-1}	Traveling	9 500.0	€
Translocation 100km	4	h	Risk	7 573.7	€
Translocation cost/km	1.5	€ km^{-1}	Variable costs total	109 336.3	€
Hydraulic oil	1.8	€ l^{-1}	Total yearly costs	159 046.7	€ a^{-1}
Hydraulic oil consumption	0.1	€ h^{-1}	Total costs/E15 hour	148.8	€ h^{-1}
Motor oil	1.2	€ l^{-1}	Unit cost	5.3	€ m^3
Motor oil consumption	0.086	L h^{-1}	Wood density	650.0	kg m^3
Maintenance 50% of deprec.	10470.6	€ a^{-1}	Cost/tonne at 40% MC	8.3	€ t^{-1}
Work travel	25000	km	Moisture content of wood	40.0	%
Travel compensation	0.38	€ km^{-1}	Energy content of wood		
Effective work hours	971	h a^{-1}	Timber with bark	1.86	MWh m^3
Working hours/shift	8	h $shift^{-1}$	Cost per energy content	2.85	€ MWh^{-1}
Workdays/month	15	day/month			
Maintenance time	97.1	h a^{-1}			
Transfer time	100	h a^{-1}			
Other working times	100	h a^{-1}			

However, the chipper was assumed to work more effectively (10%) at the terminal or plant when compared to chipping at roadside.

Long distance transportation of roundwood was assumed to be truck based with a maximum payload of 27 t. The driving speed was reduced by 25% compared to Finland in order to account for windier Scottish road conditions. Long distance transportation of chips, when chipping at roadside, was based on the similar hourly costs of the truck and the assumed load space was estimated to be approximately 83 m3 loose. The loading of chip truck was understood to be directly made by the chipper and its productivity was used to calculate the loading time. Roundtrip times were calculated in 5 km intervals from 1 to 195 km. As a new technology is introduced it can be expected that it will cause extra delays, and consequently a delay time of 10% was applied in the calculations. Transportation of chips from a terminal to the customer was based on calculations for the transport of roundwood and chips. However, terminal chipping and the consequent loading of the truck was considered to be more efficient in a terminal operation. The terminal was assumed to be 5 km from the heating plant. The values used in the calculations are presented in Table 9.

A GIS analysis was carried out to calculate forwarding distances and cost of long distance transportation for each compartment. The calculation method used, indicated that several stockpiles along the roadside should be established, as would also be the

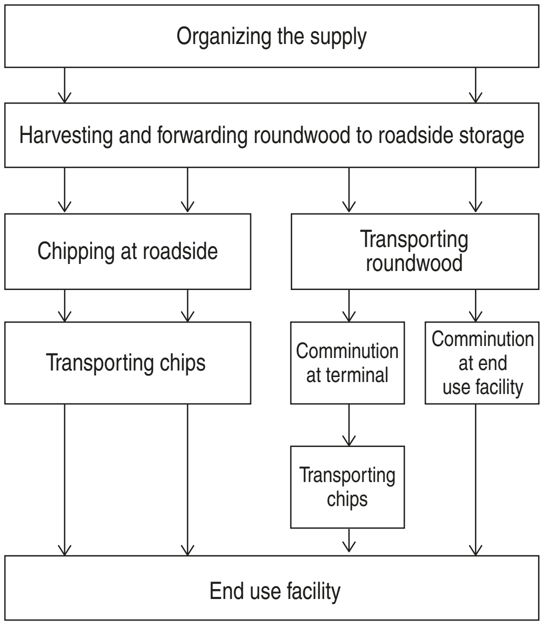


Figure 7. Production stages of different supply chains.

Table 9. Values used in the calculations of transportation, logging, chipping overheads and VAT.

Activity	Value used in calculations
Tranportation	
Load space of chip truck	83 loose m^3
Hourly operating cost of timber truck	90 Euros
Hourly operating cost of chip truck	90 Euros
Driving speed reduction factor	25%
Payload of the truck	27 tonnes
Productivity of the chipper	1.3 h per truck load
Unloading of chip truck	30 min
Weighing of chip truck	3 min
Delay times of chip transportation	10%
Loading chip truck at terminal	1 h
Logging	
Harvesting costs	12.2 Euros per tone
Forwarding costs	7 Euros per tonne
Chipping	
Moisture content	40%
Chipping	5.3 Euro per m^3
Other	
Overheads	10%
VAT	5%

case in reality. Road transportation distances for each compartment were calculated along the existing road network using ArcGIS®. Transport distances were calculated from each compartment's geographical center point (centroid) to the destination. The cumulative sum of forest areas and cumulative sums for each harvesting period according to long distance transport distances were subsequently calculated using Microsoft Excel. Variables that were scrutinized in a given cutting plan were: harvesting areas, total harvested wood, logs and small diameter material.

3 RESULTS & DISCUSSION

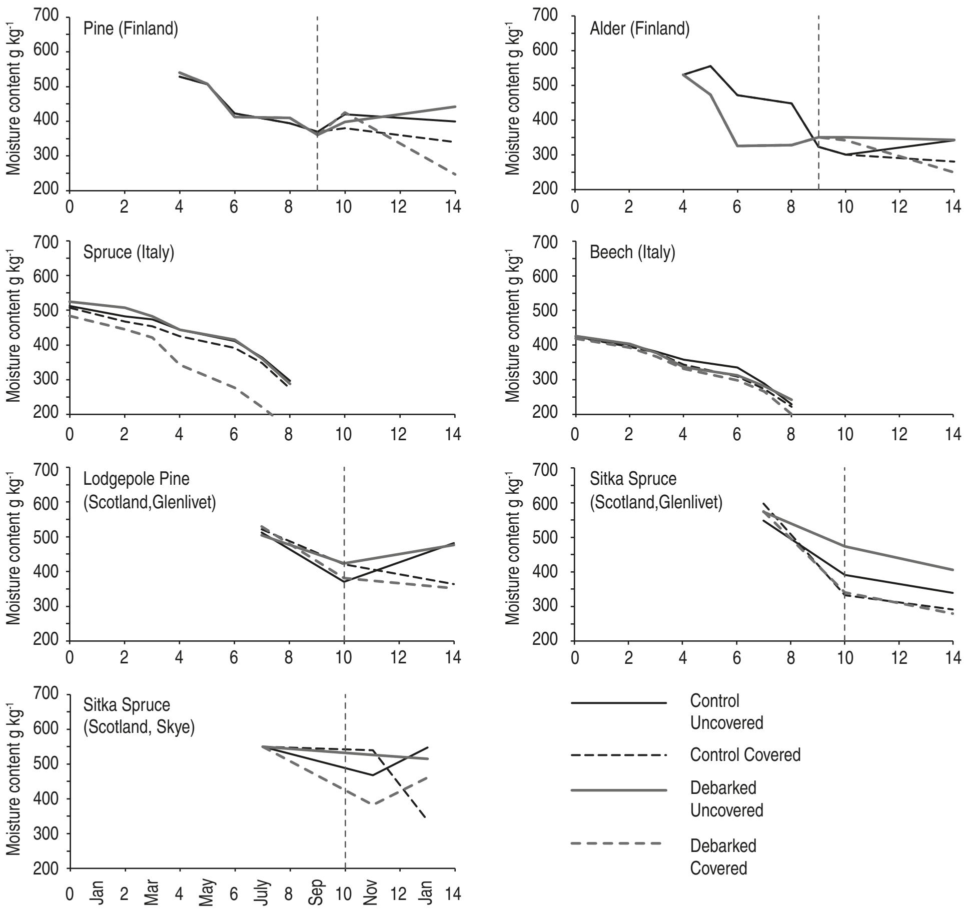
3.1 Analysis of the technical dimension (Paper I & II)

3.1.1 Drying of roundwood

The analysis of the technical dimensions in regards to drying forest biomass for energy revealed that there were large differences between the different geographic regions, species and applied treatments (Figure 8). On the Isle of Skye, the overall drying ratio was estimated to be 40 g/kg per month from May to November 2008. However, the stems were absorbing moisture (approximately 50 g/kg of wood) again during the winter month regardless of the fact that the stacks were covered. Consequently, positive effects of covering could not be confirmed on the Isle of Skye.

In the Glenlivet trial decrease in moisture content was particularly high during the spring and summer months. The decrease in moisture content was approximately 250 g/kg regardless

Figure 8. Changes in water content of the wood piles under the different treatments. Months represent 1: January 2007, 13 January 2008.



of whether the stacks were debarked or not. However, covering of the piles had a large effect since the uncovered piles dried comparatively slower. Moreover, uncovered lodgepole pine (*Pinus contorta*) absorbed moisture during the rainy period in the winter and almost reached the initial moisture content of the original samples again.

As in Glenlivet, the drying process of both pine (*Pinus sylvestris*) and alder (*Alnus incana*) was very effective during the summer months in Finland with a moisture decrease between 130 and 230 g/kg. Covering effects were similar, with a continued moisture decrease during the winter month if the piles were covered and moisture increase in the case of uncovered piles (Figure 9).

On the contrary, cover effects were not found to be as significant in the Italian trial of beech (*Fagus sylvatica*) and spruce (*Picea abies*). Moreover, in regards to beech increased debarking did not show any significant changes. However, in the case of spruce, drying was fastest when timber was debarked and piles covered.

Overall, the effect of debarking was considered to be significant in accelerating the drying process during the drying season particularly when the piles were covered (Figure 9).

However, the study revealed differences among the location of the species. The results indicate that, in Finland, debarking accelerated the drying process of alder during the drying period despite the fact that it was not covered. However, in the case of pine no effect of debarking was noted. The situation was similar to Glenlivet, where debarking did not seem to have an effect on the drying rate of lodgepole pine whereas covered and debarked piles lost more moisture than the other options both in Scotland and Italy (Figure 9).

The cover appeared to affect the drying processes particularly during the winter months, by not allowing the water to reach the logs (Figure 10). After the winter, the moisture content

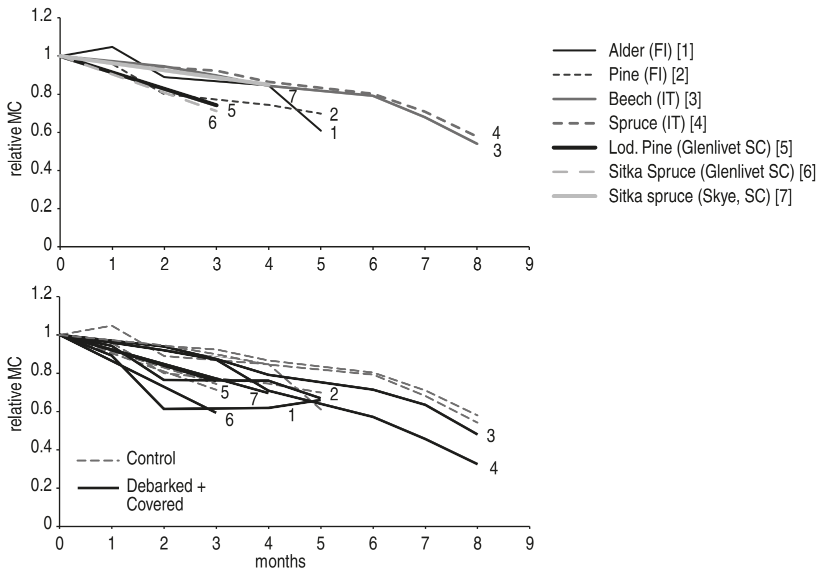


Figure 9. Pre-winter changes in the moisture content for the different locations and species in the control pile (top), and overall effect of the debarking and covering as well as the control along time (bottom). Changes in moisture content (MC) are represented in relation to the initial moisture of each trial (relative MC). Months are counted from the set-up of the experiment. Numbers correspond to same location and species.

of the uncovered piles was higher than in the end of the drying season. Furthermore, another significant finding was that the moisture content was more uniform throughout the pile if it was covered, whereas when piles were not covered there was a clear gradient from low moisture content at the bottom of the pile to high moisture content at the top (Figure 11). According to the ANOVA test, the differences concerning the moisture content in regards to location in the pile were significant for the uncovered piles (F=14.55, p-value<0.001) and not significant in the covered ones (F=1.15, p-value=0.333).

The drying of raw material to improve fuel quality has been recognized in many recent publications regarding the use of forest biomass for energy (e.g.Webster 2006, Kühmeier et al. 2007, Eberhardinger 2010, Alemayehu et al. 2011, Kent et al. 2011). The reduction in moisture content is one of the most significant quality improvements of forest biomass for energy. By reducing the moisture content, several benefist are achieved. The main benefit of drying is the increase in heating value of the raw material. There are also resulting benefits in regards to improved transportation efficiency. Furthermore, it creates fewer problems associated with the combustion of the biomass (Asikainen et al. 2002, Eberhardinger 2010). Finally, the additional benefits of decreased moisture content are the resulting lower demands for forest biomass due to the higher energy content which is also resulting shorter transportation distances. This, in

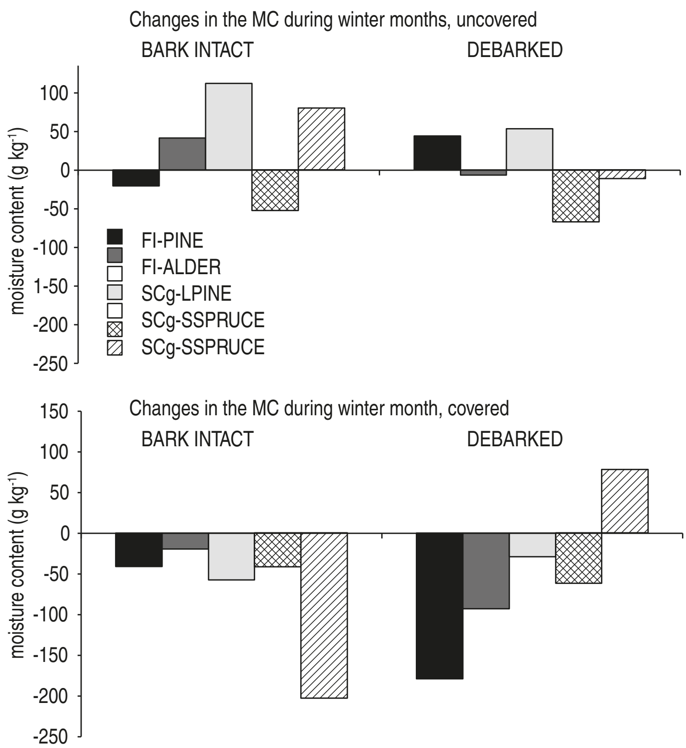


Figure 10. Absolute changes in the water content (g kg^{-1} of wood) during the winter period, for uncovered and covered piles and the two debarking treatments. FI: Sotkamo (Finland), SCg: Glenlivet (Scotland), SCs: Skye (Scotland), LPINE: Lodgepole pine, SSPRUCE: Sitka Spruce. In Sotkamo and Glenlivet, the changes are calculated for the period Oct -Feb, and in Skye, for the period Nov-Jan. Positive and negative values refer to moisture increments and losses, respectively.

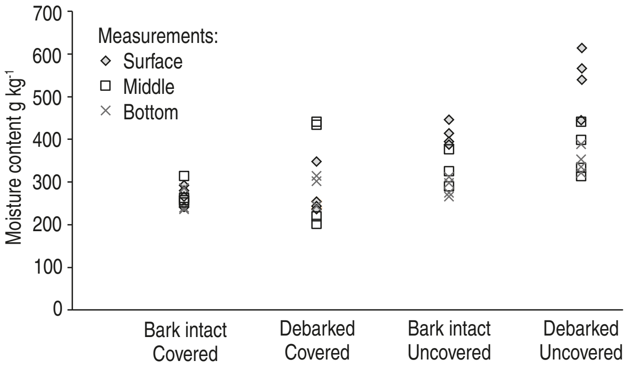


Figure 11. Differences in the moisture content according to the position of the logs in the pile. Data refers to the Sotkamo (Finland) trial, during the month of February, 2008.

return, means lower amount of traffic towards and around the heating plant, and lower CO_2 emissions of the entire production chain. On the downside, some negative effects associated with drying are potential dry matter losses due to the biological degradation of the wood, increased blade wear on the chipper, increased handling costs of the raw material, and tied up capital (Nurmi and Hillebrand 2007, Asikainen et al. 2002, Jirjis and Lehtikangas 1993).

Adapting methods of operations – debarking to promote drying

The analysis indicates that drying of raw material and subsequent improvement of operational efficiency can be increased with rather simple steps and the right timing in the production chain. The results presented in this thesis indicate that debarking, depending on the species, can have a positive impact on the overall drying results. This confirms the results also observed in earlier studies: Nurmi and Lehtimäki (2011), for example, observed the positive effect of bark removal in a recent study investigating mechanical means to promote debarking during harvesting downy birch (*Betula pubescens*) and pine (*Pinus sylvestris)*. Webster (2006) did not specifically study the effect of debarking, but observed after carrying out drying trials of Sitka spruce (*Picea sitchensis*) and Lodgepole pine (*Pinus contorta*) in Scotland, that the removal of bark would have positive effects since it would allow for improved air drying within the piles. Positive debarking effects on the drying of small energywood stems of birch (*Betula pubescens)* and to a lesser extent on pine (*Pinus sylvestris)* were also found in a laboratory studies presented by Röser et al. (2010).

There are several means to increase the debarking rate of the timber. The easiest way to promote additional debarking is by harvesting the timber during spring when sap flow is high, which will automatically remove more bark. Other mechanical options include the increasing of pressure of the delimbing knives of the harvester head, which was recommended by Webster (2006) as well. The modification of pressure of the delimbing knives to modify the debarking rate was already introduced, and found promising by Liiri et al (2005) or Björklund et al. (2008). In the case of Liiri et al. 82005) the modification was done for the purpose of minimizing debarking in pulpwood production in order to bring more biomass to the pulp mill. Another option that was studied during the trials presented in Paper I is the attachment of extra metal devices on the harvester head. Even though the initial results were promising regarding the debarking rate of the timber, more research is needed to investigate the optimal location and angle of the metal devices on the harvester head (Röser et al. 2010). Nurmi and Lehtimäki (2011) presented the results of a study where similar attachments were made to a harvester head in Finland, and concluded, contrary to the result presented in Paper I, that despite the successful debarking using the extra devices, it could not be clearly demonstrated that the extra debarking had an additional positive effect on drying compared to "normal" debarking. Another effective method to promote extra debarking compared to normal debarking during harvesting, which was applied in the research pertaining to Paper I, is to run the harvester head up and down the stem two or three times to remove extra bark. This was found to be effective in the trials presented in Paper I. However, further studies are needed to investigate the effect on the overall productivity. Nurmi and Lehtikmäki's (2011) conclusion supports the idea that before any costly investments or adjustments are made to the machine, simple steps such as adjusting the debarking knife pressure and extra movements of the stem in the harvester head should first be exhausted to their full potential.

Standardization of working methods – the importance of the right timing of biomass harvesting and establishments of piles

The results of this thesis revealed that debarking can have a positive effect, particularly if the debarking is carried out before the spring drying season, as it will accelerate the drying speed. Furthermore, Nurmi and Lehtimäki (2011) also underlined the importance of the right timing when aiming for a higher debarking rate, as their study demonstrated, that it is more difficult to debark when the stems are frozen. Consequently, operational efficiency in forest biomass harvesting operations can potentially be increased by proper planning and timing of the harvesting operations. In the optimal case, the harvesting should take place during the sap flowing season, using an above described mechanical debarking method. Moreover, piles should be established as soon as possible before the drying season, which is characterized by the high vapor pressure deficit during springtime. The significance of pile establishment was, for example, noted by Nurmi and Hillebrand (2007) and Kofman and Kent (2009) as well. Depending on the geographical location, the drying season usually starts between April and May (Röser et al. 2010).

Dissimilar material and equipment – covering to promote drying

The use of covering material to promote drying is an example of innovative materials to improve operational efficiency. The presented results in Paper I underline the importance of covering piles in different operational environments to promote additional drying of the raw material, and it is another simple step to increase operational efficiency of forest energy operations. This trend was recognized in earlier studies as well (e.g. Jirjis and Lehtikangas 1993).

A set of studies carried out in the last decade are confirming earlier trends on the importance of covering in various operational environments. In Germany, Eberhardinger (2010) demonstrated additional moisture losses of spruce crowns between 8% when compared to non-covered piles. In Austria, Kanzian (2005), in the case of logging residue bundles, reported additional moisture losses compared to non-covered bundles of 10%. The time frame of these trials was around 6 to 8 months, respectively. In Ireland, Kent et al. (2011) reported additional moisture losses in logs of Sitka spruce (*Picea sitchensis*) compared to non-covered piles of approximately 10% after 12 months of drying. Whereas, the effect of drying in the "energy wood" assortment (with roughly delimbed lengths ranging from 3 m to 4.5 m, with no minimum top diameter) for woodchip production, was not as conclusive, with more variations in the results. Earlier studies in Finland by Hillebrand and Nurmi (2001) and Nurmi and Hillebrand (2007) showed promising results in the case of birch (*Betula pubescens*), where additional moisture losses between 5 and 15% were reported. However, for pine (*Pinus sylvestris*), results were reported to be statistically insignificant. Both pine species (*Pinus sylvestris, Pinus contorta*) were found to be more difficult to dry in the drying trials presented in Paper I, and the effect of covering was not as significant as for e.g. spruce (*Picea abies, Picea sitchensis*) or alder (*Alnus incana*). Even though there are variations depending on the operational environment, species, and the assortment, the results presented in this thesis and existing literature emphasize the overall positive effect of covering forest biomass.

Adapting methods of operations – covering at the right time

The results of this thesis, as well as previous studies (Kent et al. 2011, Nurmi and Hillebrand 2007), have demonstrated that there is a trend towards the piles taking in moisture after the spring and summer drying period, and particularly during the snow melting period. Therefore, in order to minimize these effects, the covering before the winter is essential. This is particularly significant since the raw material is generally needed during the winter times, highlighting the importance of maintaining the moisture content that has been achieved during the drying season. Even though it is not possible to maintain the lower moisture content completely, the results of this study and previous studies mentioned above indicate that the covering of piles helps to maintain the achieved moisture levels. The covering of the raw material is typically a simple operation that is integrated into normal procurement operations. The covering takes place after the stacking of the piles using the forwarder or tractor that was used to bring the raw material to the roadside. No other additional machinery is needed. In the end, the cover is chipped together with the woody material. An important question is the cost of covering the piles. A study by Hillebrand and Nurmi (2004) indicated that in Finnish conditions the costs of the paper cover and the labor involved to cover the piles is recovered once the moisture content is reduced by approximately 5% using the paper cover. Nurmi and Hillebrand (2004) also noted that pile density and height of the pile have a significant effect on the covering cost, and consequently on the overall efficiency. As the drying results, when using a cover, presented in paper II indicate, the required moisture reduction to compensate the extra cost of covering can be achieved under normal practices. The cost of covering was also investigated in Germany and Austria. Eberhardinger (2010) found significantly higher covering costs compared to Nurmi and Hillebrand (2004), whereas Kanzian's (2005) calculation showed lower costs. However, it must be noted that in the calculation of Kanzian (2005), a significantly lighter paper cover was used and the cost of labor to apply the cover was not included. Despite the higher covering costs in Eberhardinger's (2010) study, it was concludes that covering can still be feasible from an economic viewpoint under the right circumstances.

Another advantage of covering that has been reported by local energy cooperatives is that under Nordic conditions, with lots of snow and ice, the covering has great advantages in keeping snow and ice out from the piles, and consequently the chips during the winter. Therefore, the covering has other positive impacts on top of reducing moisture content. In conclusion, the covering of forest energy piles is another very simple step to increase the overall efficiency of forest energy procurement operations during the winter month. In addition to this, the moisture reduction achieved by covering the piles during storage has also had positive effects on the transportation efficiency of the chips from the storage place to the heating plant by increasing the energy content per net pay load.

Standardization of working methods – using the right cover in the right place

The Eno Energy Cooperative in the Eastern part of Finland has used paper covers of different producers and noticed differences in the quality of the used papers. The most significant difference was the durability of the paper. Kent et al. (2011) made similar observations, whereas Webster (2006) reported that the cover in a Scottish trial was either damaged or blown away completely by strong winds. Consequently, the covering material itself does play an important role. During the trials in Sotkamo (Paper I), a conventional non-breathable plastic cover was used to cover the pile. Towards the end of the trial, it was noticed that in an area right under the cover mould had formed. Even though the mould did not seem to affect the drying rate, the resulting health hazards have to be considered in future applications, as was noted previously by Andersson et al. (2002).

Each operational environment has its own demands from the covering material. In Finland, snow and ice were found to be challenges in the trials carried out as part of this thesis whereas rain and wind were the greater concern within the UK trials. These findings are also supported by the results presented by Kent et al. (2011), from their experiences in Ireland. However, in Germany, Italy, and parts of Austria, lighter paper covers could be used because of less demanding environmental conditions. As a result, the development into new, innovative, and more durable paper covers is currently ongoing. Further trials, together with new, innovative covering papers, are needed to test which materials are best suited for forest biomass operations in different operational environments.

Standardization of working methods – stack open and high

Another simple step to improve operational efficiency is the proper location and stacking of the piles. This is closely related to the used harvesting methods and the forwarding of the raw material. Proper planning and the selection of the most suitable harvesting method, skid trails, and storage locations make it possible to have a positive effect on the overall operation. For example, from an operational viewpoint, operational efficiency can be improved by delimbing stems already during the harvesting operation (Laitila and Väätäinen 2011). However, the harvesting of whole trees brings more raw materials to the roadside, thereby improving the efficiency of the harvesting. The use of delimbed stems has nevertheless been favored recently, at least, in Finnish conditions. This is due to the decreased forwarding costs and easier stacking of the piles at roadside (Laitila andVäätäinen 2011), as well as to the associated environmental benefits, such as a decrease in nutrient outtake (Stupak et al. 2008). The selection of a suitable storage site by the forwarder operator is also critical, since it will determine the efficiency of the subsequent chipping operation as well as the drying rate of the raw material. The storage site should be located in a place where the chipper can easily have access to the raw material during chipping. Moreover, the importance of placing the piles in a windy, open area, is of utmost importance to promote drying, using sun and wind. The importance of the right location for drying has also been noted by Stupak et al. (2008), and Kofman and Kent (2009), Gaio et al. 2007), and in the Finnish recommendations regarding operational aspects of forest biomass operations (Lepistö 2010). Filbakk et al. (2011) and Kofman and Kent (2009) mention the importance of proper air circulation under the pile, which must be carefully considered during the establishment phase of the trial. A study by Filbakk (2011), regarding the higher moisture content in the bottom of the pile, differs from the results obtained in Paper I and by Kofman and Kent (2009), which have recorded lower levels of moisture content in the lower parts of the pile. However, despite the varying results, the recommendation to promote the air flow from below the pile is shared by all authors. The importance of stacking piles as high as possible has been previously mentioned in Finnish recommendations (Lepistö 2010) and by Filbakk et al. (2011). High piles will minimize the surface area exposed to the rain and/or snow. As a result, the area where material is drying faster should increase when the pile is stacked higher. However, when operating in different operational environments, the stacking of piles must be considered very carefully. For example, in more southern climates, where there are more sunshine days with less precipitation, it might be better to spread the material more evenly to increase the surface area that is exposed to the sun.

The above steps are a simple means to increase the operational efficiency without major investments into expensive drying equipment. Nevertheless, the easiest and most efficient way to dry raw material is by utilizing the sun, wind, and time, to its greatest potential. This is most easily done by choosing an open and windy site for the storage of raw material, and by considering the timing of all operations.

3.1.2 Chipping of forest biomass in varying operational environments

The average overall productivity of all trials in Finland and Austria was approximately 85.3 $m^3\ h^{-1}$. More detailed figures of chipping productivity are presented in Table 10.

The study revealed the close interlinkages of the chipper and the crane in regards to productivity. Whereas the species had a large effect on crane it had only minor effects on the productivity of the chipper. Conversely, the sieve size had a large effect on the productivity of the chipper and only minor effects on the productivity of the crane (Figure 12).

Both of these factors partially explain the variation in productivity. For the same grapple load size (associated with the raw material used) the smaller sieve resulted in a drop in productivity of approximately 47 m^3/h. The sieve size did not influence the effect of the load size of the grapple on the productivity (Figure 13). It is noteworthy, that when the 35x35 sieve was used in Finland the productivities were higher compared to Austrian conditions. Moreover, when using the 80x80 sieve in Austria, the productivities were lower than in Finnish operations when chipping comparable raw material.

Chipping of stems reached the highest productivity. There were no significant differences between logging residues and whole trees. The analysis of the effect of the sieves on overall productivity showed average increments of about 60% when a 80x80 sieve was used. Furthermore, the statistical analysis showed that the average productivity was about 27% higher in Finnish conditions, when the smaller sieve size was used. The close relationship of the chipper and crane was further supported when investigating the chipping of stems and whole trees with a 35x35 sieve. The results indicate that, in this case the crane is working considerably less. However, in the case of logging residues the results indicate that both the chipper and crane are working in sync after a slight “adjustment” phase at the beginning of the operations. The study revealed mixed results when chipping whole trees with an 80x80 sieve.

Table 10. Average values of productivity (loose m^3/effective hour) according to raw material assortment, results of the Tukey test (groups a and b) and test of significance for the accounted differences. Standard errors of the means are provided in parenthesis. Mean Diff = mean difference between raw material assortments.

Variable	N	Mean productivity (loose $m^3\ h^{-1}$) / Standard error		
		(a)	**(b)**	
Logging residues	34	77.9 (2.94)		
Whole Trees	3	77.4 (4.78)		
Stems	7		128.0 (4.68)	
		Mean Diff.	**SE**	**p-value**
Logging residues vs. Stems		-50.6	6.69	<0.001
Whole trees vs Stems		-50.0	5.53	<0.001

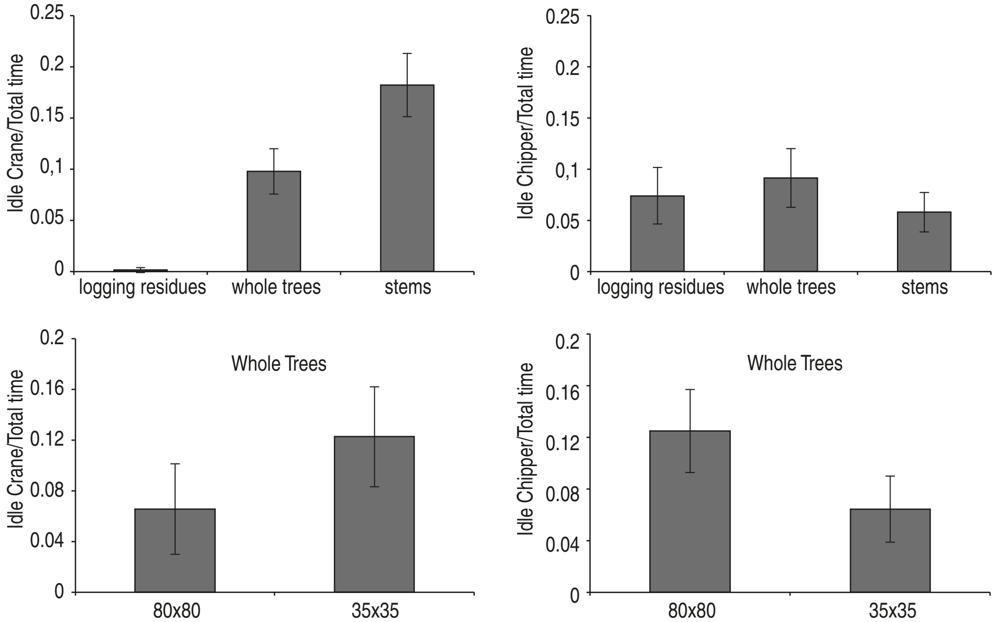


Figure 12. Average proportion of idle time for the crane (left) and the chipper (right), according to raw material assortment (top) and sieve size (bottom). Error bars represent two times the standard error of the mean.

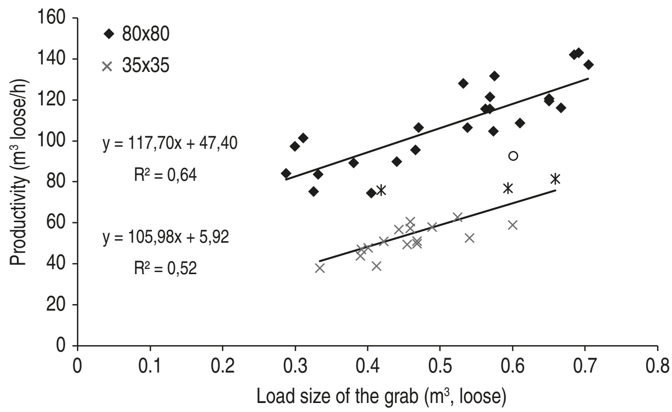


Figure 13. Productivity according to load size of the grapple, for the two sieves considered. The white dot corresponds to the Austrian test using 80x80 sieves. The darker crosses correspond to the Finnish tests using 35x35 sieves.

However, in the case of Finland the results demonstrate that the chipper was working less than the crane. As regards crane cycles it was revealed that when comparing stems and logging residues, stems were more efficient to process due to the larger grapple load consequently reducing the number of crane cycles (Figure 14). Furthermore, sieve size also affected crane cycles considerably by reducing the number of cycles when a small sieve is used. This is causing waiting times for the crane.

The efficient comminution of forest biomass is one of the key elements for the production of wood fuel (Hakkila 2004, Eberhardinger 2007, 2010). Consequently, the productive and cost effective chipping has proven to be a great challenge in many different operational environments. The vast amount of different technological solutions available to comminute

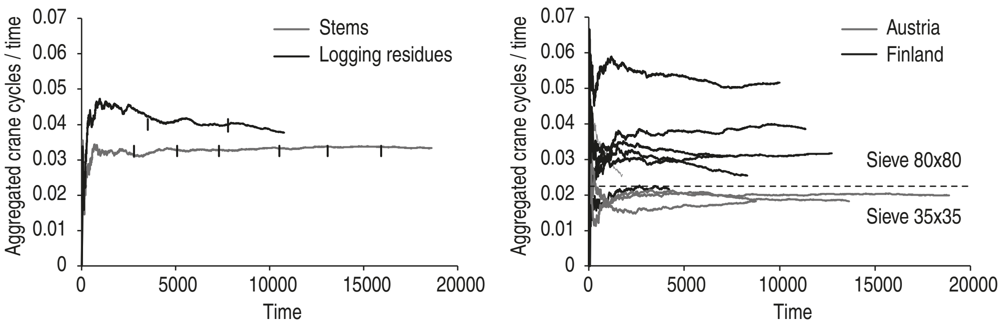


Figure 14. Cumulative crane cycles for stems and logging residues (left) and for whole trees according to sieve size and country (right). Time is expressed in cmin (1 minute equals 100 centiminutes).

biomass is another indication of the urgency and attempts to solve this challenge. These solutions include; in-woods chippers, mobile, self-, tractor- or truck powered chippers, integrated chip trucks, chippers mounted on forwarders, and stationary chippers or crushers.

According to Eberhardinger (2010), the chipper is usually the most expensive machine in the supply chain for forest biomass for energy. As a result, many studies have investigated the productivity of chipping, and factors affecting the efficiency in different operational environments, when using different comminuting technologies. Consequently, there are several studies that compare the productivity of different chippers and comminution systems. Some examples of these studies are; Desrochers et al. (1993), Asikainen and Pulkkinen (1998), Asikainen (2003), Wittkopf (2005), Yoshioka et al. (2005), Webster (2007a), Lechner et al. (2007), Cremer (2009), Eliasson (2011a), Kent et al. (2011), Kärhä et al. (2011a,b) and Pajuoja et al. (2011).

Adapting methods of operation – Chipper, crane and grapple – a close relationship

The results presented in this thesis have focused on the interaction of the crane and chipper, and the comparison of chipping energywood in different operational environments. The results presented in Paper II indicate that the efficiency of chipping can be increased by making adjustments to the existing system. In addition, the right choice of chipping equipment, crane, and grapple, is an important factor in achieving overall operational efficiency. The analysis of the data in Paper II has revealed close interlinking details between the chipper and the crane, and has also highlighted the need for the proper sizing of the chipper depending on the different raw materials. If the chipper is sized too small for a given chipping operation, it will mean that it is running at high rpm, resulting in an increase of fuel consumption and machine wear. Conversely, when the chipper is too large, it is not reaching optimal performance levels, thereby increasing the overall costs. In addition, a smaller crane will, when the operations allow, have positive secondary effects on the operation as it should reduce fuel consumption and overall stress on the equipment.

Paper II revealed the importance of the grapple in relation to productivity. There was a clear relationship between grapple size and productivity, underlining the importance of the right grapple for the right raw material in order to maximize the grapple load. The importance of the right grapple for the right conditions has also been recognized in Sweden, where a new asymmetrical grapple was found to have positive effects on productivity in different forest operations (Eliasson and Nordén 2011). It is, therefore, of utmost importance to consider the chipper, crane and grapple as one unit that is closely dependent on each other. By considering them as one unit, the whole operational efficiency of the supply chain can be improved by selecting the proper chipper and crane unit according to the majority of raw material to be processed.

The difficulty of the right chipper choice has been noted before by, for example, Spinelli and Hartsough (2001) in their review of Italian chipping operations or Naimi et al. (2006) in their review of cost and performance of wood biomass size reduction from a North American perspective. Spinelli and Hartsough (2001) concluded that engine power and the individual piece size to be chipped are essential components of chipper productivity, and have highlighted the problems associated with the infeed. These problems were most apparent when processing brushy materials. This underlines the importance of knowing what assortments are going to be chipped when purchasing a chipper, and consequently also plays a role in the decision of whether to purchase a drum or a disc chipper. The recommendation given by Spinelli and Hartsough (2001) is to purchase a disc chipper whenever the largest share of chips produced is stemwood. Regarding the disc chipper, it is more suitable for small diameter material. In North American, for example, the choices are even more difficult due to wider range of available technologies each coming with their set of advantages and disadvantages (Badger 2002). Naimi et al. (2006) concluded that disc or drum chippers, hammer hogs or tub grinders are more suitable to produce larger particle sizes (> 2.5 cm) whereas hammer mills are most suitable to produce small particle sizes (< 2.5 cm). However, an economic analysis revealed that hammer hogs are more expensive than chippers. Consequently, a thorough analysis of the operational environment and actual demands by the contractor has to take place in order to find the best possible solution for each particular case. The technology selection, therefore, remains a significant challenge of improving operational efficiency.

Dissimilar material and equipment to get it right –raw material, sieves and blades

Another element that underlines the importance of chipping, is related to the quality of the fuel chips. A large share of recent developments regarding the establishment of heating plants across Europe has been in community scale heating plants. They are usually in the range of approximately 500kW to 10 MW. In these heating plants, the quality of fuel chips is essential for a successful operation, since many have relatively narrow fuel specification needs (Kofman 2006). If these specifications are not met, it is very challenging to operate these plants in the long run since constant adjustments would be needed. Chipping is an essential element in the production of fuel chips that has a very large effect on the final product (chips). It determines the amount of fine particles, chip size, and distribution (Kofman 2006). Accordingly, the right choice of raw material, the right timing of chipping, and the chipper used, are essential components to safeguard fuel quality.

The use of a sieve is a key factor when considering the operational efficiency and fuel quality. The role of the sieve has both positive and negative effects on the procurement of forest biomass. The results of Paper II show that the chipping productivity decreases with decreasing sieve size. Furthermore, the sieve size also has an effect on the fuel consumption, as was previously pointed out by Nati et al. (2010). On the other hand, the sieve is an excellent tool to improve fuel quality. When a sieve is used, the produced chips are very uniform in their size distribution, which is one of the main quality factors of good quality chips (Kofman 2006). In this regard, the right balance has to be found to ensure chipping productivity and fuel quality requirements. In Finland, a sieve size of 80x80 is commonly used, whereas in Southern Germany and Austria, sieve sizes are usually smaller with 35x35 mm. Since the production of the smaller chips is less productive, it is consequently more costly. This is where the operational environment has a very large effect on the supply chain. In Southern Germany and Austria, the sieve size is traditionally smaller, thereby causing chipping to be a more expensive operation. Consequently by easing, in some cases unreasonably high, quality requirements of heating plants in Germany, the efficiency of the supply chains can be improved considerably. However, this can only be achieved in close cooperation with the heating plants. As a result, more active communication between the stakeholders would be needed to further improve operational efficiency. There might be heating plants where the use of larger size chips is not desirable; however, in other cases the switch towards larger sized chips would likely not pose any technical constraints, thereby increasing efficiency along the entire supply chain.

Spinelli et al. (2011a) recently investigated the option of mechanical screening to produce various grades of forest chip qualities, with promising results. The authors conclude that post chipping screening provides a cost-effective method to improve chip quality. This provides the opportunity to deliver different grades of chips to different customers, thereby optimizing the resource and satisfying the customer needs. The study by Spinelli et al. (2011) presents another means to increase operational efficiency along the supply chain, as the sieve size during chipping could be increased or sieves could be eliminated completely. This, in return, would have positive impacts on chipping productivity. However, it requires customers for all grades of chips in order to be a viable long term option.

The sharpness of the knives is another key factor to achieve a high quality end product. Even though the effect of the sharpness of the knives was not part of the study presented in Paper II, previous studies have shown that the sharpness of the knives has significant effects on both the overall productivity, and the quality of the end product (Nati et al. 2010, 2011). Operational efficiency is particularly affected by the state of the blades in two ways. First of all, overall chipping productivity decreases with increasing dullness of the blades, consequently increasing the fuel consumption.

Furthermore, the cost of the blades themselves (used quality of the steel) as well as the sharpening and changing of the blades are also factors that have to be considered. The threshold for changing blades, which has to be determined by the entrepreneur, is a challenging task. This is another example where timing is essential to ensure the operational efficiency of supply chains. In the future, more research and development is needed to assist chipping entrepreneurs with this complex analysis.

As sharpness of knives, chip size distribution is another important factor affecting fuel quality. According to Spinelli et al. (2011b), both the amounts of too small sized, as well as oversized particles, are critical to obtain good quality chips. In practice, this means that too small sized particles can cause technical problems at the heating plant, as well as health problems (Jirjis 1995). On the other end of the spectrum, too large particles cause mostly technical problems in the feeding systems of the heating or CHP plant. Chip size distribution is dependent on a number of factors, including the choice of chipper and sieve, sharpness of blades, as well as species and tree parts (Spinelli et al. 2011b, Spinelli et al. 2005, Nati et al. 2010). Stuart and Leary (1991) also found that, for example, chipper speed and whether chips are frozen or not had an effect on the quality of the end product. Consequently, chip size distribution is something that can be affected by the right technology selection, working method and timing of the operations.

When discussing the quality of fuel, the used assortments set certain preconditions, which strongly affect the end product. Commonly used assortments for the production of forest fuels are; stumps and logging residues from final fellings, whole trees or delimbed stems from thinning, and oversized or rotten stems that cannot be used by traditional forest industries (Hakkila 2004, Eberhardinger 2010, Kühmeier et al. 2007). Not all of these assortments are used in each country. Stumps, for example, are currently only used in Finland, Sweden, and the United Kingdom (Routa et al. 2012, Forest Research 2009). Stumps are usually crushed in stationary crushers at the plant, and can contain a comparatively high share of contaminants such as; soil, sand and rocks. Therefore, they are mostly used in large, combined heat and power plants (Hakkila 2004, Naimi et al. 2006). Logging residues are an assortment that is more commonly used in large scale district heating plants, because there are more impurities and they contain a high share of needles and small branches. Logging residues are commonly comminuted with large scale industrial chippers, as the quality requirements by the end user are usually low. Whole trees and delimbed stems from thinning operations as well as oversized rejected stemwood, are the preferred fuel assortments for smaller scale community heating plants, where fuel quality is important for the successful operation of the plants (Kofman 2006). From these assortments, the share of stemwood is generally larger and impurities can be limited. Both are usually chipped with smaller scale chippers using sieves which results in more uniform chip size distribution (Hakkila 2004).

Furthermore, a recent range of studies has been examining the effect of different variables on chipping productivity. For example, Spinelli and Hartsough (2001) concluded that piece size of the raw material and the engine power of the chipper are essential factors affecting chipping productivity. This was later confirmed by, van Belle (2006), Spinelli and Magagnotti (2010), and Spinelli et al. (2011b), who examined the effect of different wood characteristics on chipping performance. They concluded that individual piece size of the raw material to be chipped is the most important variable, whereas, moisture content and species were not found to have a significant effect on performance. Stampfer et al. (1997) concluded that breast height diameter, and top diameter, which also affects piece size, had a notable effect on chipping productivity. Cremer (2009), in his analysis of a large dataset in Germany, acknowledged that piece size, as well as the size of the chipper, might have an influence on productivity. However, he could not prove a significant correlation in his dataset. The conclusion of Cremer (2009) was that other factors, such as the pre-concentration of the material, was a more important factor affecting productivity.

As pointed out by Spinelli et al. (2011b), the moisture content is another variable that has been considered to have an effect on productivity; however that was not confirmed in their study. Their findings were not in line with findings by Asikainen et al. (2001), who found that productivity of chipping of fresh logging residues was, for example, higher when compared to dry residues. Kallio and Leinonen (2005) also reported moisture content as one of the factors affecting chipper productivity.

Fuel consumption is a factor that has been of interest in regards to chipping operations since it represents a major cost for contractors today. Therefore, it is of utmost importance to find ways to reduce fuel consumption in chipping operations (Granlund 2011). Van Belle (2006) analyzed fuel consumption in regards to chipping operations and recent studies by Nati et al. (2010, 2011). They confirm the initial conclusions that fuel consumption is strongly affected by piece size, the size of the sieve, or the sharpness of the blades. Consequently, by improving chipping operations in the field, it is possible to reduce the fuel consumption, and as a result, increase the operational efficiency.

Holistic planning – planning the right things at the right time

The above points underline the importance of the holistic approach to supply chain design and operation, particularly in regards to the element of chipping. As there are so many different aspects to consider, proper planning and cooperation of all involved stakeholders is important in order to be successful. Cremer (2009), for example, concluded that the pre-piling of the raw material during the harvesting and storage phase is a key component of productivity, thereby highlighting the close interlinking details of the separate supply chain links and actors. Consequently, in order to be successful, all supply chain actors have to be aware of their actions throughout the remaining steps in the supply chain. In addition, chippers are very sensitive to impurities. These impurities include sand, soil, and rocks, which will affect the productivity of the chipping. As a result, the proper handling of the raw material up to the chipping process is essential to ensure a high productivity of the chipper and to reduce maintenance breaks. This will then improve the entire operational efficiency of the supply chain. All actors along the supply chain have to be aware that the raw material should touch the ground as little as possible, and that no machine is driving over the raw material at any given point. Finally, the raw material then has to be stacked in the right place, and in a good location for chipping (see chapter 3.1.2). This emphasizes the need to improve cooperation and communication along the entire supply chain and the education and training of the labor force (see chapter 3.2.2). Another important aspect regarding the need of proper planning and cooperation according to Andersson et al. (2002), is that chipping should be delayed as much as possible in order to avoid the deterioration of the fuel once it is stored as chips (Jirjis 1995). This is causing additional demands to the entire supply chains. The use of fleet management systems and storage management applications are useful tools to optimize planning in order to increase operational efficiency throughout the supply chain. They can be used to minimize delay times in the chipping operation, which has been noted to be a considerable challenge, for example, by Spinelli and Visser (2009) or Spinelli and Magagnotti (2010). However, their application in forest energy supply chains is currently not common. The planning of operations and subsequent technology selection is also important and is discussed in more detail in connection with the social and economic dimensions in chapters 3.2 and 3.3.

Improving the work environment – operational environment affects chipping operations
This study has revealed that the operational efficiency of chipping was higher in the Finnish trials compared to the Austrian trials, even when similar sieves were used. Studies by Ovaskainen et al. (2004) demonstrated the large variations among forest machine operators. Consequently, it is one possibility that the differences are due to the fact of only having one operator in each country. However, both chipper operators were experienced and therefore it can be speculated that there are also other reasons for the difference. Another factor, besides the operator, to explain the variation in the chipping efficiency, could be varying working methods and the operational environment. For example, the more efficient organization of the various work tasks at the workplace (e.g. storage layout, chipper-truck interrelationship), as well as the organization of the work in general (information on piles, trucking, and management of the supply chain), could lead to an overall higher efficiency. It can be speculated that this is also partly due to different education and training of operators and other stakeholders (see chapter 3.2.2).

Meeting the challenges of the future
The results of Paper II as well as existing literature have revealed a number of factors affecting operational efficiency in regards to chipping. These are an indication of the complex environment in which stakeholders in the supply chain are operating. It will be a great challenge to meet the ambitious targets set by the EU to increase the share of renewable energy sources and forest biomass. In practice, this will mean that more forest chips will be produced across Europe. When increasing the use of forest biomass for energy, it will not be possible to only select the most preferred raw material and assortments. But everything that is available will have to be utilized. Furthermore, an increase in fuel prices seems likely

in the future. Consequently, the focus of increasing operational efficiency should not be on raw material selection, but on increasing efficiency by modifying the elements in chipping that we have the most influence on. This means finding the right technology selection and optimizing the maintenance of the machine to find the right balance between chipping with sharp blades and reducing maintenance costs. Additionally, the production of different chip qualities using, for example, the proper sieves during chipping or mechanical sieves after the chipping operation are simple solutions to improve operational efficiency and to satisfy demands of various customers.

3.2 Analysis of the social dimension (Paper III)

3.2.1 Organizational setup of supply chains

The setup of the supply chains in Germany and Finland differed considerably. The various actors and functional units in the supply chains of Eno (ENO) and Feldkirchen (FELD) are summarized in Tables 11 and 12. In this study, an actor is considered to be: a company, institution or stakeholder whereas a functional unit carries out a specific task in the supply chain. An actor can therefore be made up of several functional units or can act as a stand alone functional unit. The functional units are further grouped in order to lower the complexity: The Forest Owner (FO) and the Forest Authority (FA) each form a separate group. The functional units providing services to the Forest Owner are grouped in Forest Service providers (FSP). One group represents the Contractors (CON) and other functional units represent the Heating Plant (PLA). There was a significant difference in the number of actors and functional units between ENO and FELD. In the ENO supply chain there were 6 different actor and 7 functional units (Table 11) whereas in FELD the number of actors and functional units was 8 and 12, respectively (Table 12). MWB refers to MW Biomasse, owner and operator of the heating plant in FELD.

It should be noted that the reason for the timber broker to measure both the round wood and energy wood piles in the forest is to guarantee an unbiased measurement by a neutral individual. Furthermore, contrary to the supply chains in ENO the responsibility for the processing and transportation of biomass lies with the chip customer and not with the Forest Service Company (Tables 11 and 12).

The study found a large number of process items that are necessary to carry out the procurement operations both in ENO and FELD. The total number of process items in ENO amounted to 214 whereas the number of time consuming process items was 128. In FELD the respective figures were 268 and 183. The higher number of process items in combination with the comparatively high number of functional units suggests a more complex structure of the supply chain in FELD. However, the total number of process items and number of functional units is not necessarily an indication of the overall time consumption or complexity. In order to get a better overview of the process flow and responsibilities within the ENO and FELD supply chains, the various sub-processes involved in the supply chains were selected. They are illustrated in Figure 15 and Figure 16. A further simplification was carried out by grouping the functional units in 5 different groups (Tables 10 and 11).

The number of time consuming process items and number of info items produced varied significantly between the two different supply chains (Figure 17). Whereas, with the Forest Service Company in ENO, one single functional unit was responsible for the organization of the entire fuel procurement operation, similar tasks in FELD were carried out by various functional units.

Table 11. Groups, actors and functional units and their respective responsibilities in ENO.

Group	Actor	Functional unit	Responsibility
FO	Forest Authority	Forest Authority	Supports private forest owners in forest management activities, supervises operations, and can suggest forest areas to be harvested.
FA	Forest Owner	Forest Owner	Decides to do a forest management operation in their forest, for instance a pre-commercial thinning & monitors the operations in this forest.
FSP	Forest Service Company	Forest Service Company	Buys the assortment as standing timber and takes care of planning and carrying out of the procurement operation using local contractors.
CON	Logging Contractor	Logging Contractor	Logging and forwarding
	Chipping Contractor	Chipping Contractor	Chipping and transportation of chips
PLA	District heating cooperative		Customer buying the chips
		Accounting office	An active role in the monitoring of deliveries and payment of delivered chips
		Chairman	An active role in the monitoring of deliveries and payment of delivered chips

Table 12. Groups, actors and functional units and their respective responsibilities in FELD.

Group	Actor	Functional unit	Responsibility
FO	Forest Owner	Forest Owner	Decides to contract work to the local FOA
FA	Forest Authority	Forest Authority	Supports and monitors private forest owners and their forest management activities; represented by the district forester
FSP	Forest Owner Association		
		FOA Operations Supervisor	Plans the treatment of the stand; In collaboration with the district forester
		FOA Accounting Office	Accounting
	Timber Broker	Timber Broker	Measures both the roundwood and energywood piles in the forest
PLA	Energy Cooperative		
		MWB Logistics Manager	All piles on offer, checks quality and volume, and negotiates the purchase price with the Operations Supervisor; Adds pile to stock Schedules a suitable time with the Chipping Contractor & haulage company
		MWB Plant Manager	
		MWB Accounting Office	Accounting The incoming payment and matches them with their database Pays the Forest Owner and the Logging Contractor
		MWB Sales Manager	Compares delivered quantities vs. claimed quantities
CON	Logging contractor	Logging contractor	Logging and forwarding
	Chipping Contractor	Chipping Contractor	Chipping of chips
	Hauling Contractor	Hauling Contractor	Transportation of chips

Three different functional units, the FOA Operations Supervisor, the Timber Broker, and the FOA Accounting office were involved in managing the operation from finding and locating the stands to the logging operation to measuring and selling the raw material. Another three functional units, the MWB Logistics Manager, MWB Sales Manager and the MWB Accounting Office, participated in the organization of the chipping operation and subsequent accounting of it. As a result, the number of process items that occur for the organization and management of the supply chains was 103 in ENO and 146 in FELD.

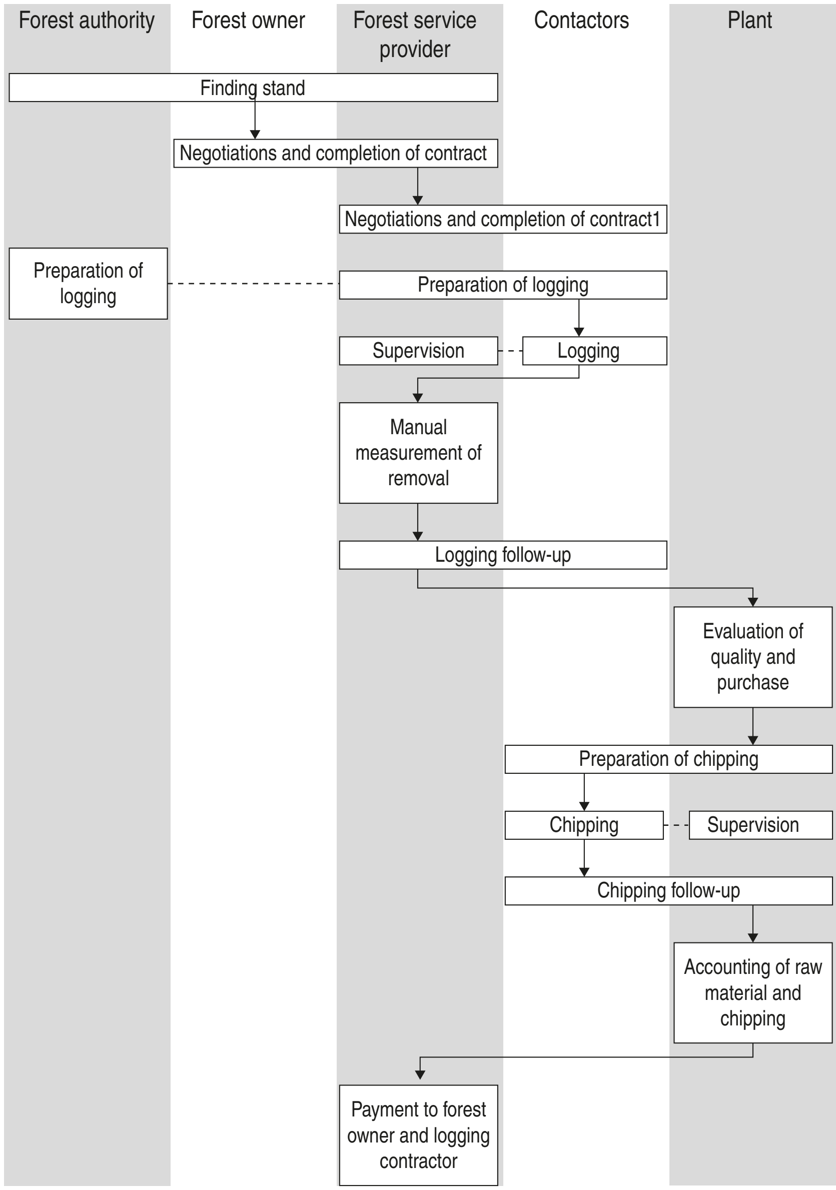


Figure 15. Business process map of the sub process in the supply chain of FELD.

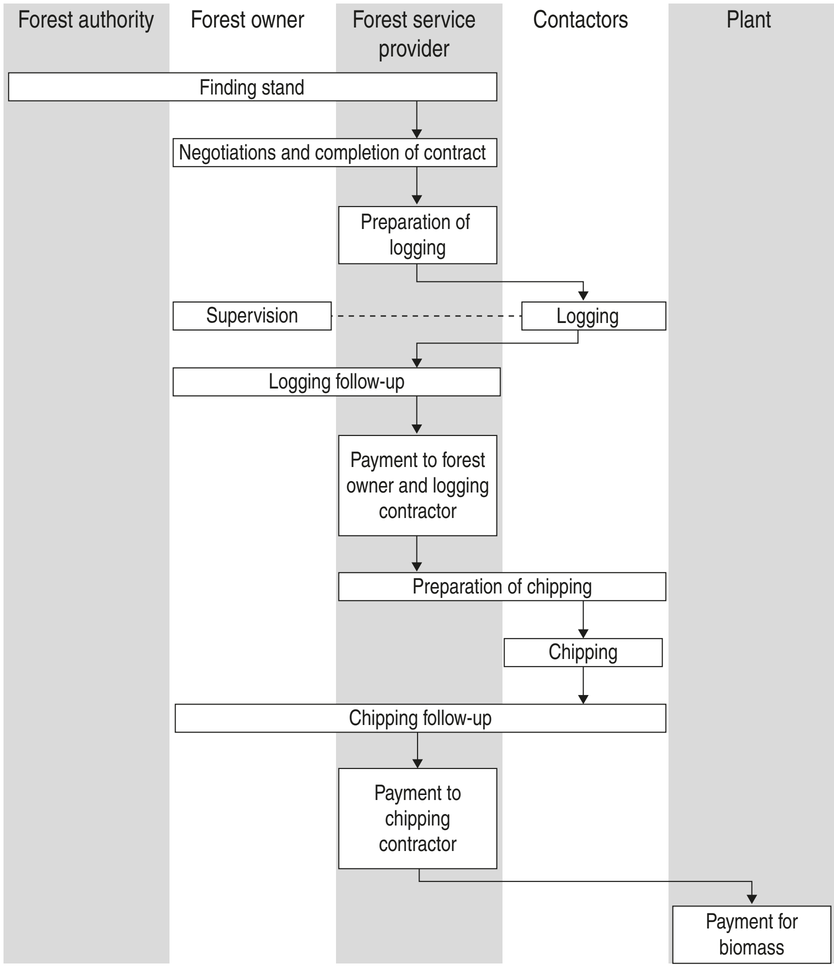


Figure 16. Business process map of the sub-processes in the supply chain of ENO.

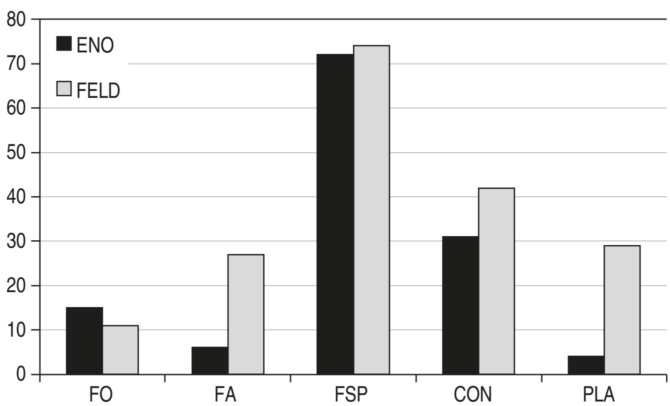


Figure 17. Distribution of the number of time consuming process items, including activities, communication, payments..., by functional unit (FO, FA, FSP, CON and PLA as defined in Table 6).

Differences in the operational environment were found particularly in regards to the selection of trees to be harvested. In Germany and subsequently also in FELD, it is common practice that the district foresters, on behalf of the forest authority, decides on and marks all trees to be cut prior to the harvesting operations. In ENO and also commonly across Finland, this decision is usually left with the logging contractors, thereby giving them more responsibilities and autonomy. Furthermore, in FELD logging sites and chipping operations are usually monitored on a daily basis by the FOA Operations Supervisor and the MWB Logistics Manager respectively. In ENO, close monitoring of the contractors is not common practice. However, in the case of ENO, the forest owners were found to be monitoring the forest operations much closer compared to FELD.

Another significant difference in the operational environment is the data exchanges between the various functional units and their interlinkages. The number of data exchanges was 66 in the case of FELD whereas in ENO data exchanges were almost half with 39 (Figure 18). However, it has to be noted that the numbers shown represent the maximum and not all of these exchanges are essentially exchanged every single time.

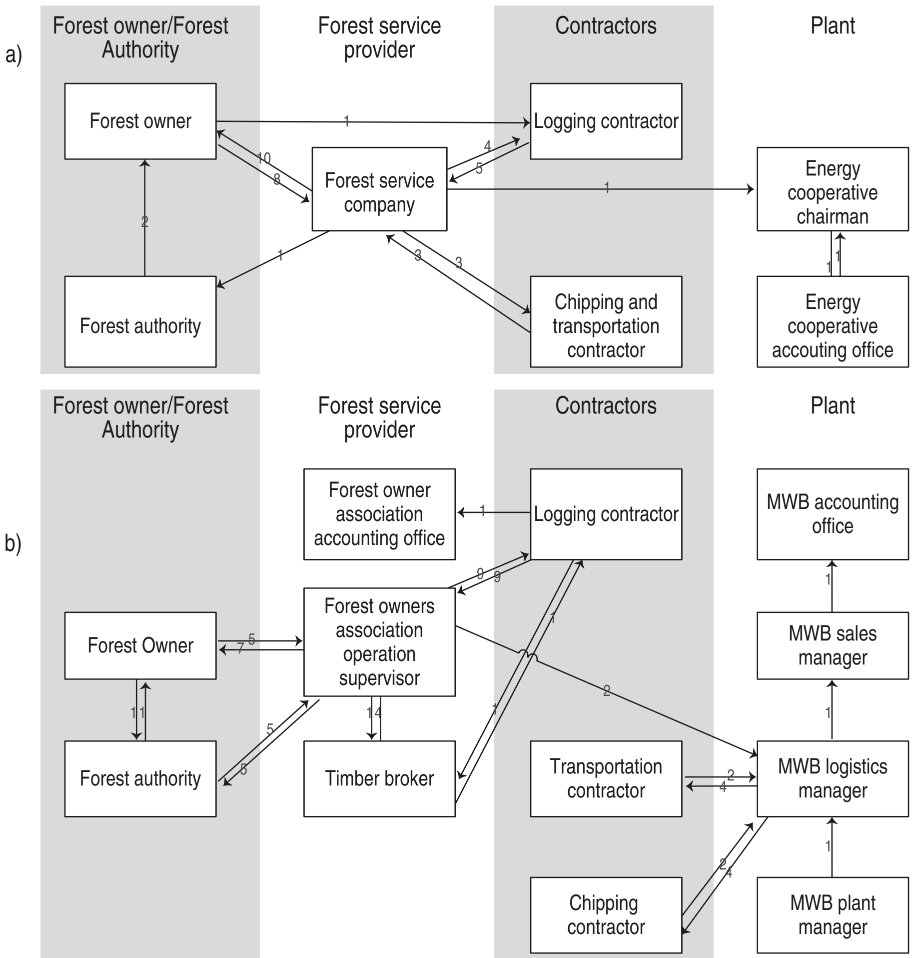


Figure 18. Number of total data exchanges between the functional units of the supply chain in ENO (a) and FELD (b). The numbers shown are totals, meaning that not all of them are necessarily exchanged every time.

Differences in the operational environment are of importance when considering the ratio of work time input and output. In Germany, stand alone harvesting operations for forest biomass for energy are very seldom and usually forest biomass for energy harvesting is integrated into the harvesting of traditional roundwood. When considering the overall output of the supply chain in FELD it reaches an average of 23 h/100m^3. This compares to an output of 24.7h/100m^3 in the ENO supply chain that is only producing forest biomass for energy.

However, when investigating the overall average time consumption of the non-productive work load (NPWL) in both ENO and FELD the situation looks a bit different. The NPWL in ENO amounted to 1335 minutes per operation, whereas in FELD the respective figure is 2071 minutes (Figure 19). The subsequent simulation study furthermore confirmed that the supply chain with the highest complexity also involved the highest NPWL. Even though the volume in ENO is not even half of FELD's the NPWL per m^3 is only a little higher consequently increasing the volume potentially is going to increase Eno's efficiency remarkably.

The share of NPWL was largest in ENO for the Forest Service Company with 710 minutes per operation. When combining similar tasks of the various functional units in the supply chain of FELD the total of NPWL in the simulation amounted to 913 minutes per operation (Figure 20).

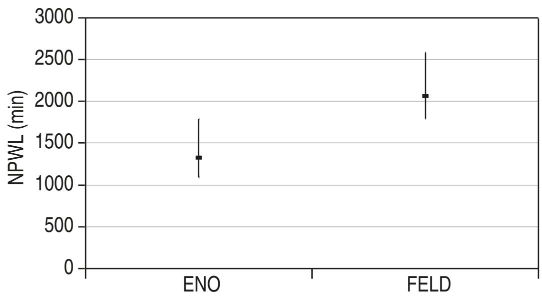


Figure 19. Comparison of the non-productive work load (NPWL) in the different supply chains. The bars show the average minima and maxima of the NPWL.

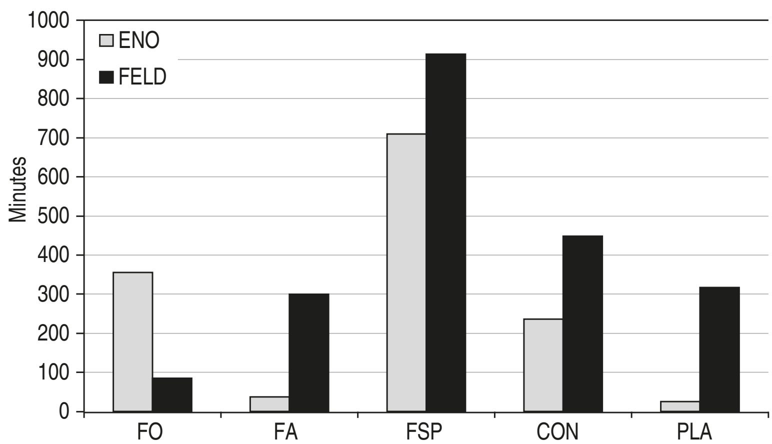


Figure 20. Non-productive work load in ENO and FELD by grouping of functional units (FO, FA, FSP, CON and PLA as defined in Table 6).

It is notable, that the NPWL in all functional units in FELD was higher when compared to ENO, which can be explained by the different operational environments. In the case of Forest Authority, the District Forester has the responsibility to visit the stand and mark the trees before harvesting and is acting as the link between the Forest Owner and the Forest Owner Association. The Logging Contractors work is also marked by higher organizational and communication efforts and more practical arrangements when compared to the respective counterparts in ENO. Finally, in the case of the plant the reason for the high NPWL lies in the fact that the functional unit of the plants was responsible for both the raw material assessment and organization and scheduling of the chipping operations.

The design and operation of efficient forest fuel supply chains remains a challenge in all operational environments investigated in this study. This is due to their complex makeup and the large number of stakeholders involved (Eberhardinger 2010, Wittkopf 2005, Gronalt and Rauch 2007, Ranta 2002, Kanzian et al. 2009, Routa et al. 2012). Weintraub and Epstein (2002) summarize the common weaknesses in supply chain management in forestry as a lack of coordination among the supply chain stakeholders and actors, poor information sharing, and exchange and resistance to integration. In order to succeed in delivering the right product to the right customer, joint planning, and coordination of the large number of supply chain actors and stakeholders to achieve the tasks and activities within the supply is essential (Ranta 2002).

Paper III offers an insight into the underlying reasons for the challenges involved in planning and operating supply chains for forest energy. The large number of processes, data exchanges, and actors, are indicators of the challenges involved. Therefore, the study introduces a quantitative method and a starting point for showing pathways to bridge the gap between the existing complex supply structures and more lean and efficient supply of forest energy in the future. The study underlines the importance of holistic planning and integration of operations to achieve the desired improvements in the supply chain.

Paper III revealed that there are large differences in the organizational setup of the supply of forest biomass for energy in Finland and Germany, due to the fact that both countries represent very different operational environments. The organizational setup of forest biomass supply to the heating plant is never identical and there are differences in the supply chains even within the same operational environments (Hakkila 2004). However, the study revealed some basic differences that are unique to each of the operational environment involved. Finland and Germany are two very different countries in respect to the importance of forestry within society (Räisäinen 1999, Schraml and Winkel 1999, Borchert 2005). Finnish people, for example, have a very close relationship to the forest since it provides both economic and recreational benefits for a large share of society. In Finland, unlike in other European countries, wood of all forest products has, beyond a doubt, the most significant effect on the economic viability of forestry (Parviainen and Västilä 2011). Consequently, this affects the way people are aware of forestry related issues within society and how forestry systems are setup.

Adapting and integrating methods of operations – building stronger networks

The different role of forests and forestry in the operational environments of Finland and Germany is reflected in the organizational setup of the two supply chains investigated in this thesis. One of the findings in Paper III is that in Germany, the district forester is more involved in everyday harvesting operations, which is also a common practice in other European countries (e.g. parts of Italy and Austria). For instance, both the selection of the trees to be harvested and the supervision of the harvesting operation are traditionally carried out by the district forester. The district forester takes several trips to the harvesting site, and communicates with the other actors of the supply chain. The situation is different in Finland, where the role of the state forester does not exist, and responsibilities are shared between different actors in the supply chain and a regulatory body. In order to improve operational efficiency in FELD, it would be beneficial to adapt and integrate existing methods of operation, and find solutions that eliminate these extra and sometimes unnecessary work processes from the supply chain. The uptake of new and more efficient supply structures is, however, facing many obstacles. In this case, state foresters have been a part of forestry operations since the start of active forest management in Germany. However, recent developments in restructuring efforts in forestry administrations across Germany have increased the size of forest districts considerably, which is making, e.g. the marking of trees prior to thinning, more challenging due to time limitations. Due to this development, such tasks are already undertaken by forest technicians, but usually only in stands with a simple stand structure and composition of tree species. This development strengthens the need for well-educated forest technicians and machine operators. The case study in Finland demonstrates that it is possible to organize the supply chain without a state forester in place. However, the challenge of overcoming long lasting traditions and practices is probably one of the greatest obstacles for the uptake of new working methods. Trust, according to Merriam-Webster (2012), is the "assured reliance on the character, ability, strength, or truth of someone or something." Building trust among all supply chain actors could be one option to overcome the challenges in regards to the state foresters in FELD. More trust in the abilities of the other actors in the German supply chain would, for instance, allow the elimination of the responsibilities of the state forester and increase collaboration of the forest service provider and operators (e.g. monitoring, double-checking activities, etc.). A lack of trust could lead to inhibit a more sensible distribution of tasks, which, in return, would result in lower costs for the supply chain. One factor that might enable increased trust is the cooperative organization of the supply chain, which is increasing in popularity for renewable energy production across Europe. The cooperative organization is discussed in more detail below.Another significant and interesting difference in the two investigated supply chains is the intensity of interest in the ongoing operations of forest owners in Finland. According to the interviewed supply chain stakeholders, the forest owners in ENO are visiting the harvesting site more often than in the case of the FELD supply chain. Based on the importance of forests in Finland, as mentioned above, the forest owner's motivation to supervise the harvesting operations more intensively could be based on two facts; the first one being an economic interest and the second being a larger interest in the ongoing operations based on a closer relationship to the forest resource. The big difference between the two supply chains is that in the case of ENO, the forest owner is contributing to extra complexity or processes within the supply chain. However, his activities do not directly affect the efficiency of the supply since they are categorized as a non-productive work load. This is different in the case of FELD, where the state forester is an active player in the supply chain. The state forester is contributing to the productive work load, and in some instances to the delays in the supply chain, affecting subsequent processes in the supply chain.

Integration of operations – reducing unproductive work elements

The large number of processes involved to get raw material from the forest to the heating plant, came as a surprise to both the authors and involved stakeholders. It has to be considered that the supply chains both in ENO and FELD are comparatively small supply chains, both feeding a municipal district heating plant of about 1.5 MW. The studied supply chains have been established based on long traditions and experiences of the involved actors. This brings both opportunities and challenges. Whereas, in many cases, the actors involved usually have optimized and developed their working methods already after a short time period the learning curve is continuing to increase at a slower rate thereafter (Björheden 2000, Purfürst 2010). Consequently, things are being done as they have always been done. The resistance to alternative ways of thinking and change within forestry (e.g. Schoene 2012) and among the actors of the supply chain are, consequently, a great challenge to improve operational efficiency. This is demonstrated in the high number of processes that are taking place in both of the supply chains. In order to make a great leap in regards to improving operational efficiency, it would therefore be necessary to start an evaluation process in which all processes are put into question with the subsequent elimination of unnecessary work elements. This should be followed by the subsequent reengineering of a new innovative supply chain, as it was demonstrated for the logistics from private forest owners to the forest industry by Bauer (2006). This will be the subject of further research in the future. Another significant finding of the study is the advantage of integration within the supply. The ENO case has demonstrated that there are benefits in terms of having only one service provider that is organizing the entire supply chain. It will reduce actors, processes and data exchanges. This, in return, will limit the number of problems, miscommunications, and delay times. A similar observation was made by Eberhardinger et al. (2009) in an analysis of strengths and weaknesses regarding the supply of forest biomass for energy in Bavaria.

Improving the work environment – business models to build trust among all stakeholders

The issue of trust among the different actors in the supply chain of forest energy has been mentioned above. Efficiency can be improved by exchanging information and mutual planning efforts along the supply chain (Mentzer 2001). However, this often does not take place due to a lack of trust among the different supply chain actors. In the case presented, more trust among the actors would enable the direct elimination of several processes, as well as eliminate unnecessary and duplicate activities (e.g. information exchanges, monitoring of harvesting operations), which is essential to improve efficiency (Bowersox and Closs 1996). Consequently, in order to improve operational efficiency, ways should be found to create a sense of unity among the different stakeholders and actors in the supply chain. This might be achieved by building more trust and a common sense of identity among all involved actors in the supply chain. One way of potentially achieving more trust among stakeholders, is the to choose a suitable business model such as the cooperative approach (Ranta 2002, GenoPortal and Juwi 2010, Brinkman and Schulz 2011). According to O'Sullivan and Sheffrin (2003), a cooperative is "a business organization owned and operated by a group of individuals for their mutual benefit". Okkonen and Suhonen (2010) summarize the benefits of a cooperative as utilizing the expertise and knowledge of each actor by sharing information, duties, and responsibilities. When everyone is working together to achieve a benefit for the cooperative, and consequently for themselves, it is unlikely that a single actor is taking advantage of the others. Furthermore, since all of the actors in the supply chains are active members in the cooperative as well, it is in everybody's interest to achieve common goals as effective as possible, which will have direct effects on the overall operational efficiency of the operations. The positive effects of the cooperative were previously highlighted by Okkonen and Suhonen (2010) in their review of different business models of heat entrepreneurship in Finland. However, Okkonen and Suhonen (2010) also note that one of the basic preconditions is the efficient operation in each link of the supply chain. Norin and Tosterud (2011), who carried out interviews with major sellers and buyers of forest fuels, also point out the partnership model, which is comparable to the cooperative model, as a possible approach to improve efficiency. The partnership model was considered to have the largest potential for laying the foundation to further advance forest fuel supply chains in Sweden. Cooperatives are a very common approach to realize economies of scale, cope with risk, and raise capital in various European countries. They come in numerous different modifications based on the business sector involved (Birchall 2009, Cooperative development Scotland 2010). The use of cooperatives has been particularly appealing for renewable energy projects. This is reflected by the fact that, for example in Denmark, 150 00 families are members of wind energy cooperatives providing 23% of Denmark's energy (Cooperative development Scotland 2010). Furthermore, in Austria, 66% of the biomass heating plants are operated by farm cooperatives, which strengthen the integration of local actors and support the regional supply chains through local value adding and shorter transportation distances (Kristöfel 2010). In Finland, the share of forest biomass district heating plants operated by cooperatives was more than 55% (Solmio 2011). The situation is similar in South Tyrol, in the Northern parts of Italy, where the number of district heating plants based on forest biomass has exceeded 30. A large share of these district heating plants was established by consumer cooperatives (Clara 2006). In Germany, the cooperative approach is also increasing in the field of renewable energies, with more than 200 solar, and more than 30 heating cooperatives (GenoPortal and Juwi 2010). In Scotland, however, the economic contribution of cooperatives has been under the level seen in other European countries (Birchall 2009), and more needs to be done to strengthen the cooperative approach in the field of forest biomass for energy.

The above examples of different countries indicate the importance of cooperatives in the production of forest biomass for energy, and it can be expected to further increase in the future. The case in ENO provides insights into the advantages of using a cooperative structure for building trust and creating the sense of identity among all supply chain actors. Consequently, it can be expected that the work environment of the various actors will be improved. This, in return, will then lead to the desired improvement in efficiency along the entire supply chain. As mentioned above, the exchange of information within the supply chain, or the cooperative, is one of the benefits of co-operative behavior. However, the efficient information and data exchange has been identified as one of the areas that need improvement. The use of modern information and technology provides one solution to these challenges and are discussed below. Even though there are a number of other business models applied in the sphere of forest biomass for energy (Okkonen and Suhonen 2010) the case in ENO is an example of the benefits of having a good business model to be successful. However, in other operational environments, it might be possible to achieve similar benefits with different business models and consequently a throrough investigation of the most suitable business model from the beginning is essential.

Dissimilar materials and equipment – use of modern technology to improve efficiency

The large number of processes, and particularly the large number of data exchanges between the different actors in the supply chain, is an indication of inefficient communication among the various stakeholders. Similar conclusions were drawn by Hug (2004), who, for example, analyzed the information flows at the forest district level in Southern Germany. By improving communication and resulting elimination of processes and data exchanges, it will be possible to improve efficiency in the entire supply chain. The uptake of modern technology to eliminate unnecessary work elements in the supply structures is one possible solution to achieve that objective. The supply chains in Finland and Germany both have a number of processes that could be replaced using information and communication technologies (ICT) tools. However, the uptake of ICT can be a challenge (Selwyn 2003, Hug 2004). The problem might be even more proclaimed in rural regions, where people are less exposed to modern ICTs. Furthermore, Patterson et al. (2003) and Hug (2004) concluded that there are considerable obstacles in terms of the integration of logistics and uptake of supply chain technology. Despite these challenges, modern ICTs were already successfully implemented in Finland and Sweden (Windisch et al. 2010, Frisk 2011), and they are finding their way into supply chain logistics in Central Europe (Linnainmaa et al. 1996, Bodelschwingh 2005, Lemm et al. 2006). However, the driving force behind these systems has been large forest companies, which are not commonly found in the supply of forest biomass for energy. Eberhardinger (2010), for example, concluded that the uptake of modern ICTs so far has not succeeded in the German operational environment due to a lack of interest by the supply chain actors, or by missing examples that prove their value (Hug 2004). Therefore, the use of modern ICTs has to be associated with apparent economic benefits in order to find their way into existing supply chains. Since Windisch et al. (2010) , Sikanen et al. (2005), and Hug (2004) all demonstrated that it is possible to achieve economic benefits through the application of modern ICT in the supply of forest biomass for energy in Finland, it can be expected that in the coming years their application will become more common. Windisch et al. (2010) claims that internet based supply chain management systems are most suitable to increase efficiency due to the associated low costs. The use of internet based systems should also support the uptake among supply chain actors due to the ease of use and common familiarity with the internet. With the adaption of this information and communication technologies, it is likely that the operational efficiency of supply chains would be improved, reducing the number of processes in the supply chains considerably. The result of Papers I, II and IV have also pointed out several shortcomings in the current supply structures that could be improved using ICT systems. The recent trend towards smartphones in society might be a positive development and contribute to people becoming more receptive toward the use of technology also in their work life.

Education of the labor force – improved operational efficiency through a better knowledge base

In the context of the social analysis linked to Paper III, several obstacles to increase efficiency have already been mentioned. They include; the need to overcome long lasting traditions and practices, lack of trust among actors and stakeholders, lack of integration of operations in the supply chain, resistance to the uptake of modern ICT solutions to optimize the supply chain, and the adoption of new business models to organize the operation and the supply of biomass energy systems. A more in-depth evaluation of underlying challenges to increase operational efficiency in Paper I, II, III, and IV, has revealed the lack of a knowledge base and the need for education and training in all operational environments. Efficiency in work is ultimately determined by the level of ability and knowledge (Nieuwenhuis 2002) which underlines the importance of education and training of the labor force in order to overcome these obstacles. According to Norin and Tosterud (2011), future developments should focus on the training of all involved actors in the supply chain, which will, consequently, strengthen their in-depth understanding. Training and education has benefits for countries that already have established supply chains by improving the efficiency of existing operations (Johannesson and Björheden 2011). The training and education of actors in operational environments, without existing knowledge about the use of forest biomass for energy, is even more important, since it will safeguard the proper use of technology and methods and at the same time support efficient supply chains. Jirikowski (2005) summarized the benefits of a better education as; having a shorter training period on the job, proper use of the machines, higher work safety, and higher efficiency through limited downtimes of machines. A recent study by Thorsén et al. (2010), in

Sweden, has investigated the effect of a training course on experienced harvester and forwarder operators. It was concluded that even a two day training course can have significant positive effects on the efficiency. Thorsén et al. (2010) also concluded that with continuous training, it is possible to stop harvester and forwarder operators from falling back into their old routines. The supply of forest biomass was demonstrated to be a complex structure (Papers I–IV), and in many cases, solutions that are used in the procurement of round wood, other supply chain solutions, or business models, cannot be directly implemented in forest biomass supply chains (Okkonen and Suhonen 2010, Sikanen et al. 2005, Eberhardinger 2010). However, it is the actors on the ground that have to carry out the actual work, and therefore, their education and training is a very effective method to raise awareness about the unique challenges associated with the supply of forest biomass for energy. The education and training of stakeholders has proven to be a very successful method to ensure uptake of the latest research efforts by actors in the field, and to actively support the technology and know-how transfer. Numerous EU funded projects such as NorthernWood Heat 2004–2007 (NWH 2012), PelleTime 2008–2010 (Pelletime 2012), 5 EURES 2005–2007 (5 EURES 2012), EUBionet II 2005–2007 (EU Bionet II 2012), and AFO 2009–2012 (AFO 2012), have demonstrated the positive effect of education and training at the grass roots level, and contributed to the successful implementation of supply chains for forest energy in different operational environments (e.g. Röser 2007). Furthermore, Kärhä et al. (2011c) also recognized the need for improved training and education in regards to mechanical thinning and developed educational material directly aimed at improving the efficiency of multi-tree handling.

By better understanding the relationships among the different stakeholders, actors and applied technologies it should be possible to overcome long lasting traditions and work practices. However, in order to change something, it is essential to understand why it is worth changing and what the associated benefits of the change are. This understanding can only be conveyed to stakeholders through education and training. A good example of such efforts on a national level is by Skogforsk in Sweden. Johannesson and Björheden (2011) report about a successful campaign to improve efficiency and quality aspects in the supply of logging residues for energy production. Their training course focused on the proper methods, technology, planning, and ways to improve cooperation among the various stakeholders. The positive effects of this training have already been noticed in practice with improved efficiency in logging operations of about 5–10% (Johannesson and Björheden 2011). The high demand of such training and education efforts was reflected in participation figures that have already doubled from the originally anticipated levels. In the future, these kinds of training and education efforts should contribute to build trust among the supply chain actors and open new pathways to improve operational efficiency by adapting the different methods of operation. In relation to trust, mentioned above, Paper III has revealed that in the case of ENO, and more generally speaking, in Finland, the decision of which trees to cut is left to the harvester operator. Whereas in FELD, and more generally speaking, in Germany, the decision of which trees to cut is with the district foresters. The fact that the state forester is going to the stand to mark which trees are going to be cut, represents a significant extra effort in the supply chain that is often delaying the entire harvesting operation (Paper III). However, in Germany, many foresters are reluctant to give the decision making power to the harvester operators, because it is, in some cases, assumed that harvester operators do not have the necessary knowledge to make that decision. This is, of course, a relevant concern. For example, in Austria, in the early 2000's, only 10% of the harvester operators had a relevant education (Jirikowski 2005), which highlights the challenges faced in everyday forestry operations. In Finland and Sweden, this problem has been countered by the intensive education and training of harvester operators.

Juntunen (1995) and Gellerstedt and Dahlin (1999) reported that harvester operators receive a comprehensive education that prepares them to face an increasingly demanding environment, which includes a basic understanding of ecological issues. The training of harvester operators has a long tradition in Finland and Sweden due to a much earlier and advanced mechanization of forest operations, whereas the mandatory education of forest operators in Central Europe is a rather recent development. Naturally, there is a range of other factors affecting the operator capabilities, such as different stand structure and species composition in the different operational environments. However, the ENO case is a good example of the benefits of having educated supply chain actors that have the knowledge to carry out a range of duties to the highest expectations. The findings from papers I–IV also point to the fact that improvements in the operational efficiency of supply chains can be achieved by putting more emphasis on the education and training of all involved stakeholders. Paper I has demonstrated that it is possible to promote the drying of forest biomass by making minor adjustments in the organization and operation of the supply chain. However, the knowledge transfer through education and training of the labor force is essential to implement the recommendations given in relation to Paper I, thereby ensuring improved operational efficiency in the long run. The conclusion from Paper II and IV is that more focus should be put into the proper education of all stakeholders in the supply chain, but particularly forest machine entrepreneurs to optimize working methods and support the integration of operations. The different working methods and integration are known to have a significant effect on the productivity of harvesting (Harstela 1993, Andersson et al. 2002, Hakkila 2004, Ovaskainen et al. (2004), and consequently on chipping operations. With the proper investment into operator education, the operational efficiency of forest energy operations can be increased significantly in the future.

Asikainen et al. (2008) have indicated a large increase in the need for forest harvesting, chipping, and transportation equipment in the next 20 years in order to meet the objectives of the EU’s 20/20/20 targets. However, in order to meet the targets, it will be necessary not only to increase the number of machines, but also to put a strong focus into the training and education of forest machine operators. If the operational efficiency of forest energy supply chains can be improved by increasing the productivities along existing supply chain, it will mean that fewer machines and fewer operators are needed.

3.3 Analysis of the economic dimension (Paper IV)

3.3.1 Feasibility of forest biomass for energy in the Scottish Highlands

The availability analysis in Paper IV showed that there were sufficient forest resources in the surrounding area of the district heating plant to be established in the town of Wick. However, harvestable volumes were found to be comparatively small in the first years before a steep increase in available forest biomass is expected in the year 2012 (Figure 21).

The Scottish Highlands are marked by a highly unique operational environment with a large share of very moist soils where it is necessary to use the logging residues as a brush mat, and the fact that there is a lack of competition for timber. Once logging residues have been used as material for a brush mat they cannot be used for energy production anymore due to the impurities. These exceptional circumstances result in the fact that roundwood can be used for the production of energy (Figure 23). The use of roundwood has further advantages as local harvesting entrepreneurs are already familiar with the harvesting and processing of roundwood.

In the overall cost comparison of the location of chipping, it was found that chipping at the plant would be the most beneficial option. Chipping at roadside was found to be the second cheapest option up to a transportation distance of approximately 100 km after which the establishment of a terminal close to the utilization facility (< 5 km) would become the cheaper option (Figure 22).

However, the operational environment always largely effects the location of chipping. After considering the above mentioned options in light of the operational environment it was concluded that chipping at the roadside is the most suitable option for the northern part of the Scottish Highlands due to the fact that a number of additional customers are expected in the future and chipping at the plant is out of the questions due to noise restrictions as the plant would be located in the middle of town. The establishment of a terminal was seen problematic due to the lack of a suitable location and the extra handling costs (Figure 23).

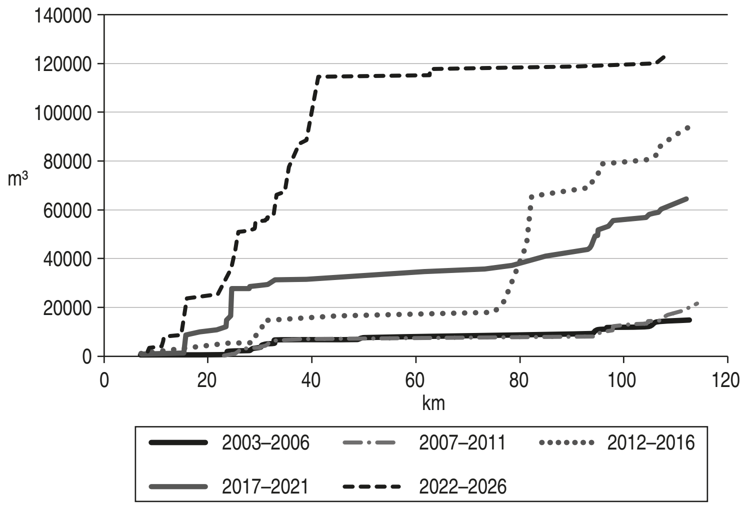


Figure 21. Cumulative yearly harvesting volumes by road transportation distance. Years 2003–2026.

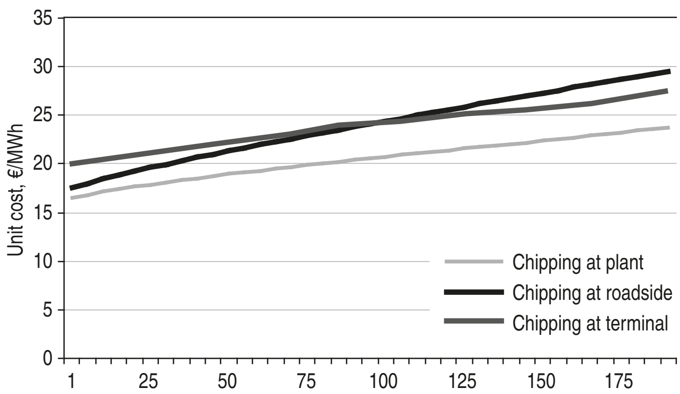


Figure 22. Unit cost of energy according to different locations of chipping.

Furthermore, the fuel quality requirements were additional selection criteria for the design and consequent feasibility of the supply chain (Figure 23). It was concluded that the fuel requirement of the largest share of the customers would be very high due to the relatively small size of the boiler installations. In the case of a gasification plant the fuel requirements would be even higher since the gasification system would need an incoming moisture content of less than 15%. The storage of the raw material before processing is not only important in terms of fuel quality but it is particularly important in regards to long distance transportation. Figure 24 indicates the high sensitivity of the overall costs to transportation.

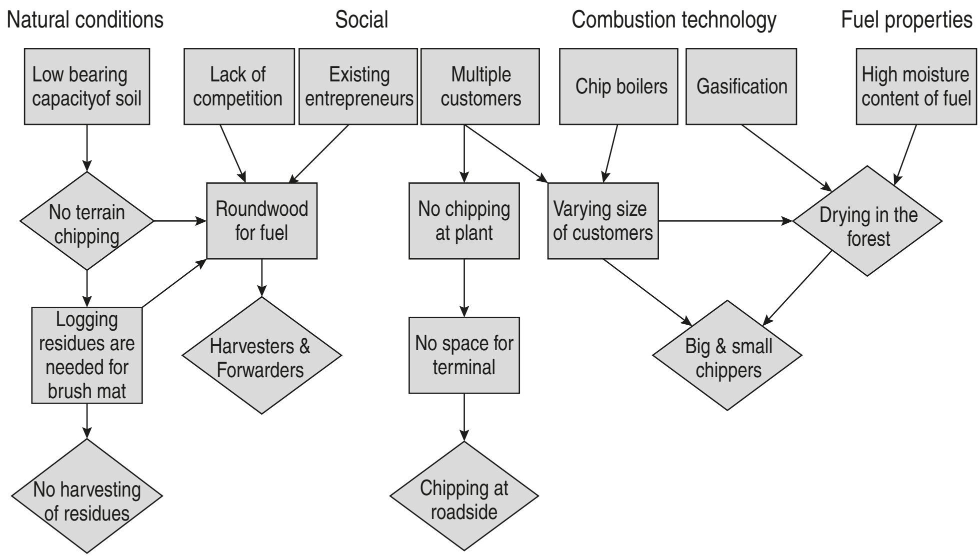


Figure 23. Decision support tree for forest energy harvesting in the case of Northern Scotland.

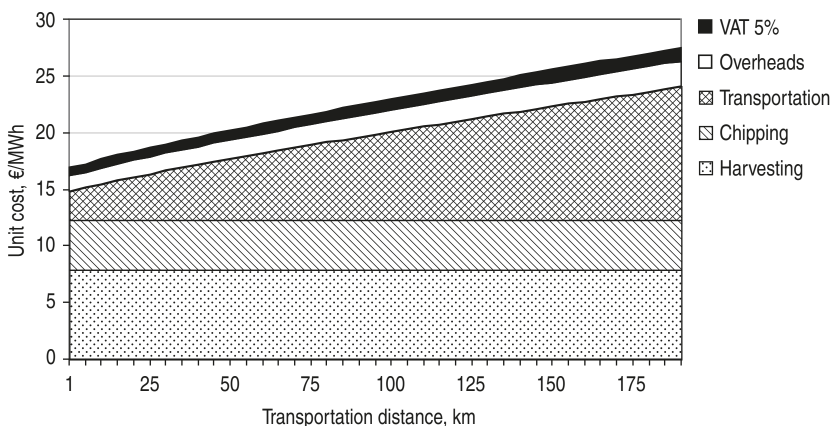


Figure 24. Estimated unit cost in €/MWh of forest fuels when chipping is done at the roadside.

The use of forest biomass for energy is linked to a number of social and environmental benefits that are often highlighted when promoting the utilization of local forest resources for the generation of heat and electricity (Röser et al. 2008). However, the economic feasibility is the key foundation that has to be maintained in order for projects to become successful both in the short and long term. Nevertheless, there can be an exception to the rule in the case of small scale heating plants of communities, or church institutions, where ecological or symbolical ideals (e.g. use of "local" resources) are valued higher than economic principles (Eberhardinger et al. 2009).

The economic performance of supply chains for forest biomass depends on a large number of factors that have been previously summarized as the operational environment. However, the economics of the supply chain will eventually determine their success or failure. Therefore, the in-depth knowledge about the operational environment, particularly in a new setting, is of utmost importance to make the right decisions. The results of Paper IV indicate that there are a large number of variables that have an influence on the economic viability of supply chains.

Adapting methods of operations – estimating biomass availability

Raw material availability is an essential aspect of economic viability, as the raw material availability will determine the supply costs of the raw material to the heating or CHP plant. Whenever making economic feasibility studies, the availability of raw material should be the first item to consider, since it sets the limits to the sizing of the heat or CHP plant. Sizing of the plant is, of course, initially based on the energy demand of the town or municipality. However, if the demand of the plant exceeds the sustainably available biomass, the plant has to be downsized accordingly. There have been numerous studies to estimate the availability of forest biomass for energy in Europe, and the general understanding is that there is a large potential in the future to increase the use of forest biomass for energy (Nikolaou 2003, Alakangas et al. 2007, Asikainen et al. 2008, Mantau et al. 2010). Yet, there is large variation within each country, and sometimes even within the region, and therefore these studies only give a general overview. Consequently, it is of utmost importance to carry out regional availability studies to get detailed cost-availability information both in the short and long term (Asikainen et al. 2008). In these calculations the ability of the heating or CHP plant to pay for raw material also has to be considered as it has a big effect on the availability of biomass. Examples of such case studies, to determine the available resources and their associated procurement cost at plant level, can be found from across Europe (Röser et al. 2007a/b, Sikanen and Röser 2007, Virkkunen 2008, Röser et al. 2009, Anttila et al. 2011, Asikainen et al. 2011a).

The importance of transportation to safeguard operational efficiency has already been mentioned in chapter 3.1.2. If transportation distances get too long, in order to procure the necessary annual fuel demand of the plant, it is necessary to either adapt the size of the heating or CHP plant accordingly, or to accept a higher fuel price. This was demonstrated in the case of Chaumont, in France where it was concluded that relatively long transportation distances would have to be tolerated in order to the needed amounts of fuel (Röser et al. 2009, Virkkunen 2008). Other factors of the operational environment influencing the availability of forest biomass are the availability of secondary and tertiary residues, tree species, and forest types (Röser et al. 2008). For example, according to Röser et al. (2008), the logging residues in Finland are available at a low price, whereas thinning residues have to be harvested before their utilization at comparatively high harvesting costs. Furthermore, when harvesting logging residues of Norway spruce (Picea abies), the availability of residues per hectare is considerably higher when compared to Scots pine (Pinus sylvestris). These examples show that raw material characteristics can have a significant effect on the overall availability of raw material. Consequently, they must be carefully considered when making availability studies. The case of Scotland underlines the effect of the operational environment on the availability of fuels. Since there was no significant competition for the forest resources, the harvesting and chipping of roundwood for energy was an option. In other operational environments this would have never been a viable economic option due to other competing industries, e.g. particle board, pulp and paper and sawmilling (Ilavsky et al. 2007, Asikainen et al. 2011a). Furthermore, in the case of Scotland, it is not possible to utilize logging residues due to the low bearing capacity of soils which limits available forest fuel sources even further. With an increase in the demand for timber due to the ambitious climate change goals the UK government has set, the situation in the Northern Highlands of Scotland might change considerably in the future. It is therefore essential not only to ensure short term economic viability, but also the long term supply of forest biomass to the heating plant. Future trends in the development always have to be taken into account and detailed sensitivity analyses are essential. The availability of forest biomass for energy highlights the great challenges from an economic perspective when planning supply chains in a new operational environment. This makes project based availability analysis an essential component to ensure the operational efficiency.

Standardization of working methods – use of proven and reliable technology

The availability of proven and reliable technology, as well as expertise in the operation of the technology, is another essential variable to be considered in both existing, and new operational environments. Paper IV illustrates the benefits of having the harvester-forwarder system already in place as an established harvesting system. In most cases, the use of existing technology and know-how has positive effects on the operational efficiency since operators don't have to learn a completely new technology. Asikainen et al. (2011a) noted in their investigation of supply chain establishment in Poland and Scotland, that whenever similar base machines can be used, it has benefits in terms of limiting additional investments and reduced overall risks. The uptake of a completely new technology, and the use of harvester and forwarders in particular, is very challenging, and the adaptation takes a long time (Ovaskainen et al. 2004, Purfürst 2009), which in return will affect operational efficiency. This does not mean that the utilization of innovative technology is not desirable, per se. But in new operational environments, where local stakeholders have limited experience, the introduction of innovative, unproven technology, may cause extra challenges that can be avoided. However, in a situation, where an established market is already in place, challenges related to new innovative technologies might be buffered more easily. Contrary to Scotland, in Poland, it is not common to use harvesters and forwarders. This affects the availability of technology and know-how to operate these machines, in order to produce forest biomass for energy. Laitila et al. (2009) also concluded that the production of logging residues in Poland is a challenge due to the lower degree of mechanization in the country. It is possible to integrate proven technology and know-how in forest biomass operations, thereby contributing positively to the overall efficiency and reduce risks (Asikainen et al. 2011b). There are a number of varying definitions of integration within forest harvesting, describing different levels of integration (Pottie and Gaumier 1986, Hudson and Mitchell 1992, Hakkila 2004, Ranta 2002). However, in the context of this work, integration refers to the situation where stakeholders in the supply chain can benefit from existing and proven operations and do not have to learn a completely new method. The case of Scotland demonstrates that harvesters and forwarders are already commonly used to carry out harvesting operations, and the procurement of timber will not pose any challenges to existing operators. The only new aspect that has to be integrated into the supply chain to produce forest chips in Scotland is chipping.

In Northern Scotland, it would be necessary to develop a suitable harvesting system for logging residues that ensures that forest machines do not sink into the ground. In the current system, the logging residues are used as a mat to drive on. Cable yarding systems for flat terrain, which are currently under development, would be an interesting, yet expensive technology solution in the future. Even though the prospect of such a system sounds promising, the cost efficient application is not granted since their application has not been proven in practice. Therefore, investing in cable yarding systems for flat terrains would carry a high risk because there is no local expertise in operating such a system. Consequently, the performance both in the short and long terms remains an unknown. As a result, existing proven technology should always be preferred over a new, unproven solution, without an existing track record. Examples of such systems are; bundling machines, which have been praised as a solution to the low bulk density of logging residues (Andersson et al. 2002, Timperi 2003, Hakkila 2004). However, even though global interest in these machines has been high due to the associated optimization and logistics benefits, their application, in practice, has been limited, and a challenge in many operational environments due to the lower than expected performance of the machine (e.g. Kanzian 2005, Spinelli and Magagnotti 2009, Eliasson 2011b, Kärhä and Pajuoja 2011, Eberhardinger 2010). Another new technology development was a bundler for raw material coming from early thinning (Nuutinen et al. 2011). This technology was supposed to make thinning operations more profitable, but trials in Finland indicated that even though the technology and associated working methods were promising, initial results indicate that it is not cost-effective in practice and developing work is continuing (Kärhä et al. 2011d). The case study presented in paper IV was based on proven reliable technology, with a positive track record in other operational environments. This was done in order to avoid any future pitfalls in the supply of forest biomass to the customer(s).

Proven and reliable technology is also essential for the heating plant side of the operations. The chosen combustion technology is another aspect of the operational environment that has a great effect on the overall economics of the supply chain. In the case of Wick, where the case study in paper IV was based, the selected technology was a gasification system, which is setting very high demands on both the gasification equipment and the supply chain. This is because the supply chain has to deliver clean and uniform chips of approximately 35% moisture content to the plant on a continuous basis. The incoming moisture content of the plant should be approximately 11%. The difference between the delivered moisture content (~35%) and the needed incoming moisture content of the gasifier (~11%) has to be removed by artificial means. Consequently, if the moisture content of chips can be reduced using natural means cost savings can be achieved. This kind of specific chip quality requirements set special conditions on the supply chain, and consequently, it might be necessary to purchase more expensive equipment to produce the required product. In return, this will mean that the customer might have to pay a higher price for the desired higher quality product. The combustion equipment not only sets limitations to the fuel supply, it can also be a limitation by itself. In the case of Wick, the CHP plant had to be scrapped because the technology chosen was not "capable of reliably and economically fulfilling its objectives" (SVT 2009). Finally, the equipment of the district heating plant was auctioned in the fall of 2011 (BBC 2011). This is a case where the use of proven technology to provide heat for the district heat customers would have most likely led to success, as it has in many cases around Europe. Consequently, the use of proven technology on both the supply and the plant side are essential to maintain operational efficiency in every operation.

A thorough investigation of the technology to be used and the needed know-how for its operation is a precondition in each operational environment. The case study presented in Paper IV was exactly such an effort, yet the project failed due to several shortcomings in the planning and implementation of the project. A positive case where both proven technology and existing expertise was used to establish a supply chain for forest energy was carried out in Iceland. In that particular case, a supply chain, based on existing technology for roundwood harvesting, was adapted so that local operators were able to run the entire supply chain based on previous experiences. The case study by Sikanen and Röser (2007) was carried out during 2007 and the production of forest biomass and establishment of the heating plant followed in 2009 (Skógrækt ríkisins 2009).

Integration of operations – finding the right technology

The study about the Scottish Highlands depicts the complex interrelationship of proper storage, chipping, and social considerations to safeguard the operational efficiency of forest biomass supply in the area. The operational environment in the Scottish Highlands is particularly vulnerable to failures along the supply chain. This is due to the above mentioned fact that the established heat plant was a gasification plant which had special specifications in regards to moisture content. Consequently, the proper storage of the raw material along the supply chain is essential due to the fact that the remaining moisture content has to be extracted using more costly artificial means. Furthermore, due to the location of the heating plant, positioned in the centre of the town, it is not possible to chip directly at the plant, which would have been the cheapest option (Paper IV). Due to these challenging circumstances, the close cooperation among all the actors in the supply chain is even more important than under normal circumstances, and needed in order to ensure an efficient supply of biomass which meets the requirements of the customer (Ranta 2002). The essential part in this remains the chipping operation. Due to the fact that roundwood is harvested for energy purposes, it is necessary to invest in a bigger chipper that is able to handle large diameter trees .The fact that the gasification plant needs a very uniform chip size sets even more quality requirements for the chipper. As highlighted in chapter 3.1.4, the careful selection of a suitable chipper, based on the raw material to be produced, is essential. It was also found to be a challenge in the presented study. The situation is made even more complex by the fact that the chipper entrepreneur might face challenges in the future when more assortments of biomass from, e.g., private forests, become available or when the number of customers with varying demands increases. The challenge to maintain operational efficiency will be to find a reliable chipper that is able to produce various ranges of fuel qualities, thereby guaranteeing a full utilization rate, or investing in a very specific machine that produces a perfect product for one customer with a lower utilization rate. A detailed economic analysis of all the supply chain links, as is presented in the study, is essential to guarantee operational efficiency of the entire supply chain in the short and long term. A different study of a Scottish estate interested in producing forest biomass for energy highlighted the challenges linked to the selection and the feasibility of a chipper (Röser et al. 2007b). The study investigated the annual amounts to be produced for their own utilization and concluded that it would not be profitable to invest into a chipper unless other customers for forest biomass in the area were found. Even in that case, a small versatile chipper would be needed to meet the varying quality demands of different customers.

Adapting methods of operations – logistics management to improve operational efficiency

The logistics and management of supply chains of forest energy is an essential key to efficiency (Ranta 2002, Andersson et al. 2002). Therefore, it is crucial to either improve existing practices or organize supply chains in new operational environments according to the highest standard possible. The calculations presented in the study indicate the vulnerability of the supply chain to cost fluctuations, particularly in regards to transportation, which is an essential component of logistics. Transportation efficiency is very sensitive, and dependent on a number of factors, such as; the load volume of the truck, the raw material itself and its density, the moisture content of the raw material, and finally the transportation distance (Ranta 2002, Hakkila 2004). As a result, transportation remains one of the greatest challenges, particularly when dealing with the use of forest biomass for energy due to the low bulk density of the raw material (Eriksson and Björheden 1989, Hakkila 2004). Traditionally, the end product coming out of the forest has been solid wood, as a raw material for sawmilling and timber production. However, in forest energy supply chains, the actual end product produced and transported is energy. Consequently, the supply chain has to be adapted in order to ensure delivery of a high quality end product and efficiency of the supply chain (Andersson et al. 2002). In order to improve the operational efficiency particularly when dealing with raw material of a low density, it should be comminuted, preferably before transportation in order to maximize the delivered load up to the legal weight and dimensions of the truck and/or road. Furthermore, Ranta (2002) points out the importance to reduce or eliminate the handling times whenever possible, and the need to coordinate the dependency between the chipper and the truck in case of roadside chipping. In the largest share of supply chains across Europe, these objectives are achieved by chipping the raw material at the roadside with subsequent transportation to the heat plant (Diaz-Yánez 2011, Asikainen et al. 2008). This was also confirmed by several case studies in countries across Europe (e.g. Laitila et al. 2009). Another essential factor to ensure efficient transportation is the reduction of moisture content before transportation. The importance of moisture content reduction in regards to transportation has already been investigated in numerous previous studies in different operational environments (Eberhardinger 2010, Sikanen 2010, Kühmeier et al. 2007, Wittkopf 2005). All studies conclude that by reducing the moisture content to approximately 30%, a considerable amount of cost saving can be achieved in comparison to transporting fresh wood which is typically between 50–60%. Various methods to reduce the moisture content are discussed in chapter 3.1.2. Through the reduction of the moisture content of the raw material, prior to transportation, the share of energy transported per truckload is augmented. However, the proper sizing of the transportation vehicle is essential to find the right balance between reaching the maximum payload and the size of the load space. The selection of the transport system is affected by a number of factors depending on the operational environment. These factors include; the quality and structure of the forest and long distance transport road network, conditions at the forest landing where the raw material is stored or chipped, and the facilities at the heating plant (Andersson et al. 2002). For example, the establishment of proper unloading facilities and trucks with moving chain floors has been a simple but effective solution to increase operational efficiency, at least in Finland. Due to varying operational environments and the large number of demands on the transport systems, their selection might not always be based on solely economic considerations from the supply chain point of view (Andersson et al. 2002). Particularly in community scale heating plants, system flexibility, and the possibility to integrate the selected transport means into other operations outside the forest (e.g. the use of containers), are also significant selection criteria. This has also been demonstrated in Paper IV, where annual production volumes in the beginning of the development were considered to be low. As a result, the multiple usage of equipment would have tremendous benefits until production volumes increase. Consequently, the selection and adaptation of the transport system on a case-by-case basis is essential to ensure an efficient supply chain of forest energy.

In the calculations presented in Paper IV, it would have been the most efficient option to transport the logs directly to the heating plant for further processing at the plant, thereby achieving the highest bulk density possible. However, due to the circumstances in the operational environment, such as the location of the heating plant being in the middle of town, and the higher overall costs of a terminal, it was concluded in the study, that the most effective way of procuring the biomass was chipping at roadside with direct delivery to the plant. In reality, however, it turned out that the entrepreneur was able to find a terminal outside the town of Wick, where the logs were stored and chipped (Reforesting Scotland 2007). This is an example and indication of the variable effect of the operational environment on practical decisions within the supply chain and underlines the statement of Ranta (2002) that there is "an obvious need to take a total supply chain perspective when planning any single activity in the chain rather than considering that activity in isolation". This statement by Ranta also supports the benefits of a holistic three-dimensional approach to investigate forest energy suppply chains. The analysis of the social dimension already discussed the associated positive benefits on operational efficiency of limiting extra processes and overlapping work tasks. The case of the Northern Highlands is a good example where one actor, the entrepreneur, was in charge of the entire supply chain from the forest to the plant. A comparison between Finland and the Scottish Highlands revealed large differences in the transportation efficiency due to the road weight limitations, speed limits, and road conditions. The lower weight limitations in Scotland (38 tonnes), compared to Finland (60 tonnes), had a significant effect on the transportation economy when comparing the two operational environments. Furthermore, the road network in Finland was considered to be consisting of wider and less winding roads than in Scotland. These factors affect the driving speed and the kind of base vehicles that can be used. They also have a great influence on the overall economics and efficiency, and must be investigated carefully to find tailored solutions for particularly challenging cases. A suitable solution to a similar transportation problem in mountainous conditions was presented by Röser et al. (2009) in a case study near Granaglione, Italy. In the case study, a typical Finnish chip transport truck was tailored to be able to operate in the operational environment of the Granaglione region. The case study also demonstrated that despite the initial high investment costs, the truck would be a viable solution if a certain threshold of annual chip production would be achieved. Kent et al. (2011) found surprising results in regards to the use of tractors and trailers for chip transportation in the Irish operational environment, and highlighted the need for further research to investigate optimal transportation systems for different regional operational environments. Eberhardinger (2010) also showcased several tailored transport solutions to address barriers to operational efficiency in different operational environments. In Finland and Sweden, road weight limits, as well as truck dimensions, have been traditionally higher compared to the rest of Europe (International Transport Forum 2011), which is making transportation more efficient. Furthermore, people have gotten used to these vehicles on the road, and therefore, it is not an issue that is discussed very much, at least in the public domain. The resistance to change is particularly strong in Germany, where larger truck dimensions and weights are currently tested. There is considerable skepticism among experts and the public (Nürnberger Nachrichten 2011) despite the fact that similar trucks are already commonly used in Sweden and Finland. At the same time, even larger transportation vehicles with high gross vehicle weights are currently under development in Sweden (Löfroth 2011). This is a good example of the large effect of the operational environment on actual operations. Despite the fact issues related to transportation play a significant role, it is also recognized that they are challenging to change or influence and it needs strong cooperation between authorities and manufacturers.

The improvement of logistics and management of supply chains of forest energy is a key component to ensure the operational efficiency of supply chains. As already pointed out in chapter 3.2.2, the application of modern technology is one possible solution to improve the operational efficiency, and consequently, the economic performance of the forest biomass supply chain (Windisch et al. 2010, Ranta 2002). In regards to logistics, modern technology solutions such as the global position systems (GPS), navigation, and route optimization solutions, as well as fleet management systems, are particularly suitable in regards to logistics and transport. These solutions have are already been applied in Sweden, on an experimental basis (Frisk 2011).

Improving the work environment – forest biomass and the public domain
The operational environment is also very much affected by the social structures and attitudes of the public. For example, the recent interest in green energy sources in Europe has lead to a situation where customers of electricity are willing to pay an extra supplement in order to purchase "green" energy (PKS 2012, Vattenfall 2012, Energis 2012). This demonstrates the willingness of the public to pay an extra price in order to achieve objectives they consider important. These influences of the operational environment have a great effect on the overall economic performance since it allows for more flexibility. Whereas, a given project might not be economically feasible only based on a pure cost-benefit calculation, the willingness of certain groups within society to pay more for a desired product, in this case environmental friendly produced heat and/or electricity opens the way for new business models. For example, investors and operators have more flexibility to plan and establish heating plants, and realize projects that otherwise would have not been feasible purely from an economic standpoint. On the contrary, the social aspects of the operational environment can have negative effects on the economic performance of supply chains. Recent discussion on the overall suitability of wood as energy, with particular focus on whether the use of wood is carbon neutral or is associated with negative environmental effects, can have negative effects on the overall economic performance of the supply chain. These negative effects are mostly reflected in higher harvesting costs due to the exclusion of certain stands and/or biomass assortments. Consequently, this is resulting in higher transportation costs. Furthermore, the need for special harvesting systems with lower environmental impacts, affects the overall economics of the harvesting operation. In some extreme cases, the social aspects of the operational environment also have the capability to stop entire projects from realization. This is why the importance to use proven and reliable technology cannot be overestimated. The case in the town of Wick has demonstrated the negative outcomes the wrong selection of technology may have. The failure of this CHP plant will most likely cause many people to associate forest biomass for energy with the failure in Wick. This means that new projects, even though based on better and more suitable technology, are likely to face more opposition and more scrutiny from the investors, policymakers, and the public. A case where stakeholders have taken a very proactive approach in communicating their project to the public is in Matapedia, Canada. Local stakeholders have formed a consortium of different local stakeholders all supporting and contributing to the efficient use of forest biomass for energy. This consortium has visited several existing proven solutions across Europe and tailored them to their local needs. At the same time, the consortium has pursued a very active communication and outreach strategy informing the public about its activities and the reasoning behind it. The communication strategy also involved comments by independent research organizations that gave their view on the developments in the region. This has lead to a project that has experienced great support from the local public, as well as national recognition in regards to establishing a reliable supply chain and heating plant that is

contributing to rural development and renewable energy sources (Legare 2011). The case in Matapedia serves as a good example of the developed three-dimensional approach as it also dealt with the important element of timing and planning. Due to the high volumes of snow it is not possible to chip at the roadside during the winter time. Consequently, it was necessary to adapt the supply chain according to the operational environment and find alternative solutions to ensure the best timing of chipping operations.

The feasibility of supply chains for forest energy is, as described above, dependent on a large number of factors. However, policy might also have an effect on the operational efficiency of forest biomass supply (Ranta 2002, Kallio et al. 2011). This is another important aspect of the operational environment that has to be carefully considered. This was demonstrated recently by the German Government, with the decision to terminate the use of nuclear energy in the future (Bundesrat 2011). This is likely to have an impact on the use of forest biomass for energy since more energy will have to be produced from alternative energy sources. The policy aspect calls for a detailed case-by-case analysis of the effect the political decisions will have on regional or national availability and the consequent cost of forest biomass delivered to the plant.

3.4 Evaluation of the results

The chosen method of approaching the topic from a technical, social, and economic viewpoint, as suggested by Sundberg and Silversides 1988, and by adopting Pfeiffer's (1964) assumption that operational efficiency can be improved by adopting different means, has its strengths and weaknesses. Sundberg and Silversides (1988) state that knowledge about operational efficiency should be, in the ideal case, quantitative and presented in figures. Furthermore, it should be "systematic in the sense that is coherent, consistent, and verifiable" and in a format in which it is easy to understand for all involved stakeholders. Also, Sundberg and Silversides (1988) recognize the challenges and difficulties encountered when dealing with operational efficiency, and accept a certain level of uncertainty and imperfection which can also be found in the work presented in this thesis. They state that "to make a wise decision with imperfect knowledge is precisely the true distinction of a good manager, but it is also one quality to use the knowledge that is in fact available". This thesis examined and further developed a holistic three-dimensional approach and related it to supply chains for forest energy. The proposed approach aims to be a contribution to the knowledge base and to enable better decision making of all involved stakeholders, thereby increasing operational efficiency in their operational environments.

The aim of the thesis was to investigate and improve operational efficiency of forest biomass supply chains in different operational environments by examining a three-dimensional approach in which forest energy supply chains are investigated from a technical, social and economic perspective. The thesis demonstrates that the chosen approach was practical to investigate the complex relationships between the chosen technologies and different supply chain actors and stakeholders thereby contributing to maintain or improve operational efficiency of forest energy supply chains. Due to its applicability in different operational environments, the approach is also suitable in a more global context. Furthermore, it captures the effect of different aspects and characteristics of the various operational environments on the setup and organization of supply chains as, for example, demonstrated in Paper IV. This will be valuable knowledge to ensure or improve operational efficiency when adapting exsisting forest energy supply chains or when building up supply chains in new operational environments.

The proposed approach, as illustrated in Figure 25, follows an increase in complexity from the technical dimension, where the separate supply chain links are examined, to the social dimension with a focus on the organizational setup of supply chains. Finally, the economic dimension is taking an even more complex viewpoint as the overall feasibility is evaluated. The three-dimensional approach was found to be a practical tool to improve operational efficiency as it serves two different purposes. It allows for an in-depth analysis of each dimension and thereby contributes to a better understanding thereof. Furthermore, the framework allows maintaining a view of the larger picture which enables to place findings in the bigger context of the entire system (Figure 25).

The technical dimension addresses the separate supply chain links such as harvesting, storage, chipping and transportation. The examination of the technical dimension revealed six main features that should be considered. 1) Careful raw material selection to meet customer demand and to ensure performance throughout the entire production chain. 2) Selection of a suitable harvesting method taking into account fuel quality aspects (e.g. delimbing, debarking). 3) Storage management (location, height, exposure) and use of suitable materials to promote drying (e.g. covering paper). 4) Selection and application of suitable processing technology (sizing of chipper and crane, sieve size, sharpness of knives). 5) Handling of the raw material throughout the supply chain to minimize contamination.

The social dimension investigates the organization of the supply and the way all actors in the supply chain interact and communicate with each other. The analysis of the social dimension discovered five main features to be considered. 1) The training and education of all actors in the supply chain. 2) The implementation and uptake of modern information and communication technology. 3) The identification and subsequent elimination of non productive work elements in the supply chain. 4) Establishment of business models that build

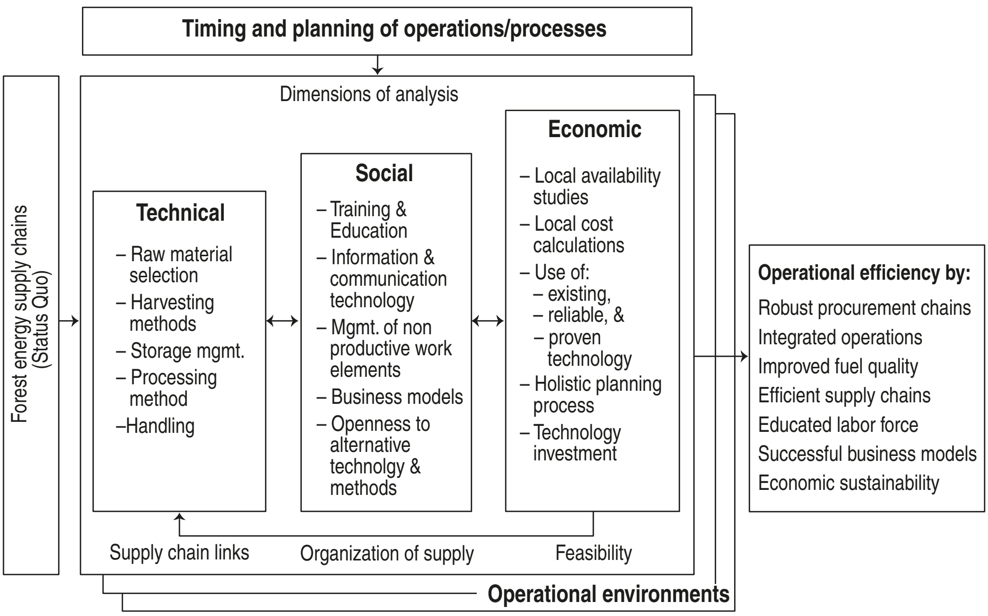


Figure 25. Three-dimensional approach to examine and establish forest energy supply chains.

confidence among the different actors in the organization and operation of supply chains. 5) Create an environment that allows for flexibility and alternative thinking in regards to technology and working methods.

The economic dimension takes an even larger viewpoint as it investigates the all-encompassing feasibility of forest energy supply in the operational environments. The investigation of the economic dimension exposed five features considered to be important to ensure operational efficiency. 1) The importance to carry out local fuel availability studies prior to plant establishment. 2) The need to carry out local cost calculations based on the operational environment. 3) The use of existing, reliable and proven technology. 4) Holistic planning efforts to capture the various aspects of the operational environment and its effects. 5) Careful selection and investment into technology needed to produce the desired fuel quality.

The benefit to consider the different dimensions is that it allows gaining a broader understanding of the challenges at different stages of forest energy supply chains and how they relate to each other. By having this understanding of the different dimensions it is possible to develop holistic solutions that support and improve operational efficiency not only at individual stages but that are applicable to the entire supply chain.

The thesis has also demonstrated that it is necessary to add another component to the original three dimensions proposed by Sundberg and Silversides (1988) namely timing and planning (Figure 25). The analysis of the case studies in the context of the three-dimensional approach revealed the importance of proper timing and planning of the different operations and processes. The technical dimension, in particular, is very sensitive to timing of the operations, eg. in the case of establishing storage piles or deciding when to cover them. However, also the social and economic dimensions are sensitive timing questions when planning the organization of supply or considering the reliability on punctual deliveries.

As the analysis of the case studies presented in Paper I–IV has shown the application of the described three-dimensional approach should eventually lead to improved operational efficiency in a given operational environment by creating robust procurement chains, integrated operations, improved fuel quality, efficient supply chains, an educated labor force, successful business models and economic sustainability (Figure 25).

The results presented in Papers I–IV have been validated by earlier studies, but this work is unique in the way that the study is taking a more holistic approach to supply chain design. It is also considering the operational environments and effects of various supply chain's interlinking details on the overall operational efficiency. However, the conclusions drawn are based on a relatively small number of observations and a limited cross section of different operational environments. The presented general trends are, however, apparent, and relevant new findings are presented. Furthermore, until now, few efforts have been undertaken to better understand and improve the operational efficiency of forest fuel supply chains in different operational environments.

The harvesting phase of the procurement operation is not included in this study despite the fact that the cutting and consequent forwarding of timber is an essential phase in procurement operations. However, the investigation of the harvesting of forest biomass from thinning was not within the scope of this dissertation. This is because these are complex operations that have been dealt with in earlier studies (Belbo 2011, Eberhardinger 2010, Laitila et al. 2010, Kärhä et al. 2011, Di Fulvio and Bergstöm 2011, Webster 2007b). Today, the felling phase is still considered the most demanding and costly operation in the production of chips from thinning operations (Laitila 2008). There are also several drying and chipping studies, but comparative studies similar those presented in Papers I – IV are not as common. There are also limitations in terms of the geographical approach. The studies presented are restricted to a number of countries, and in order to obtain an even better result to support the general objectives of this study, it would have been better to carry out even more studies in different operational environments. However, the studies presented are focused on some of the main developing markets in Europe, each facing different challenges and operational environments. Furthermore, the literature review allows to draw more solid conclusions and to put the results of the presented case studies into context with existing research findings. The use of existing literature counteracts the challenge of having limited case study data, and, as in the case of chipping operations, a limited amount of operators. The presented thesis, despite the limited amount of studies, demonstrates that by proper planning of and adjustments in the forest energy supply chain, great improvements in the operational efficiency can be achieved.

3.5 Future perspectives and research needs

The importance of delivery of the right quality of fuel to the customer at the right time is important for the future success of forest biomass for energy if it wants to establish itself as a viable option next to fossil fuels. The three-dimensional analysis has highlighted various shortcomings of existing supply structures that are obstacles to improving operational efficiency. For example the examination of the technical dimension exposed challenges in regards to handling and storage to ensure high quality fuel chips. Therefore, further research into the use of covering paper for drying trials is needed to test new paper types and mixtures that are better suited for the drying of forest biomass. Furthermore, the effect of sieve size on bulk density of transportation is another issue that could have potential impacts on transportation density. Consequently, the breakeven point between decreased chipping productivity and increased transport efficiency should be the focus of further research efforts in the future.

Moreover, the importance of the right selection process of chippers for each individual situation is important because operational efficiency can be improved if a suitable chipper with the optimal crane and grapple is working for a large proportion of the work time. Therefore, research efforts in the future should focus on developing tools that assist forest entrepreneurs in their decision of which chipper, crane and grapple to purchase. Today, entrepreneurs are often not familiar with the latest research results or technological developments. Tools to bridge that gap are necessary to better support chipping entrepreneurs, which will then result in improved operational efficiency. Furthermore, automated assistance measures for the operators of chippers on e.g. crane movement, would also be desirable. This would enable more efficient working and reduce stress on the machines. Another aspect of the technical dimension was the sharpness of knives, which is essential to ensure productivity and consequent operational efficiency. In the future, more research and technology development is needed to provide more information for the operator, for instance, about the current state of the knives. A prediction tool to determine the sharpness of the knives, depending on the raw material, would be very useful for operators. Also, sensors able to determine the knife wear and give the entrepreneur a warning, would be a great step towards more efficient chipping operations in the future. More research is also needed to determine the optimal time to change or sharpen knives, and to find the right balance between maintenance costs and lost productivity due to dull knives. Finally, more research about the material and steel quality used to produce knives could be beneficial in order to produce higher quality knives in the future.

There has been some development in the estimation of moisture content during the chipping, or blowing process of chips. This is another area where more developments would benefit the entire supply chain by allowing for better information flow among all involved actors, thereby eliminating work phases at a later stage. It is known that moisture content and chip size affects the bulk density of the chips. Future research should focus on the question of how to best optimize the moisture content and chip size in order to achieve the highest bulk density in transportation, thereby, improving the operational efficiency of the entire supply chain.

The analysis of the social dimension indicated that the total number of activities in the supply chain has to be reduced to effectively improve operational efficiency. Research efforts should, therefore, focus on the development of more efficient supply structures that are supported by information and communication technologies. The aim of these research efforts should be on the reduction of non productive workloads in the supply chain, the integration of activities, and the elimination of unnecessary activities. The measurement and description of key indicators of the supply chain remains a challenge to quantify improvements. Consequently, it would be beneficial to also apply methodologies commonly used in other supply chain management disciplines, such as the supply-chain operations reference-model (SCOR), to forest energy supply chains.

Despite the technical developments, in the future, more research and practical efforts have to be made to improve the training and education of all involved stakeholders in the supply chain. A supply chain is always as weak as its weakest link; for that reason, future efforts should focus on the development of education and the training of all stakeholders in the supply chain. Many efforts have already been undertaken, but more focused action to develop training courses and materials are needed, particularly in countries where the use of forest biomass for energy is only at the beginning of the development. Furthermore, solid communication strategies to promote the use of forest biomass for energy are needed. The implications regarding the utilization of forest biomass for energy, at all levels, must be highlighted from the beginning. Active communication from the start is essential to inform the public about the consequences, implications, and benefits of the actions taken in a given project. This will strengthen the support of the public and erase fears about a technology that the general public usually knows little about.

Based on the results of the analysis of the economic dimension, it was revealed that the knowledge about underlying factors that cause unnecessary work elements, and thereby decreasing the operational efficiency, is indispensable information when building a technology transfer model for forest biomass for energy. For that reason, the results presented in this study are useful, as they dissect why some procurement operations are more efficient than others. Okkonen and Suhonen (2011) have also highlighted the challenges of transferring know-how and technology between regions in relation to business models of heat entrepreneurship. However, at present, there is no clear theoretical background for the successful transfer of technology and know-how, particularly in regards to the use of forest biomass for energy. For example, Saralehto (1986) and Bozeman (2000) have provided a theoretical background for technology transfer, while Sikanen and Asikainen (2004) have taken a first step to adapt the existing models for cut-to-length harvesting operations. The results of this thesis have discovered that the operational environment is an important factor in regards to the design and establishment of forest energy supply chain. In order to be successful in the setup of supply chains in new operational environments, it will be necessary to further expand the research into the successful technology and know-how transfer. The next step should be to develop a theoretical technology and know-how transfer model to optimize the use of forest biomass for energy in different operational environments. The demonstrated complexity of municipal scale supply chains is causing many failures due to a lack of proper planning and information. In the future, more needs to be done to communicate best practice examples and to inform all involved stakeholders and actors on how to avoid commonly made mistakes.

4 CONCLUSIONS

The thesis is built around a number of experiments and case studies to evaluate a three-dimensional approach to improve operational efficiency of forest energy supply chains in different operational environments. The thesis has found several benefits of the three dimensional approach. It has global applicability as it allows investigating supply chains in different operational environments. The three-dimensional approach also increases understanding of the effect of the local operational environment and allows local stakeholders to adapt their operations. Furthermore, the three-dimensional approach allows for an in-depth technical analysis at each link of the supply chain while also maintaining a view of the social and economic dimensions, which are of a broader nature. Finally, the chosen approach revealed the importance of timing and planning of operations and processes for all three dimensions investigated. Consequently, the timing and planning of supply chain operations and processes should be the common denominator when applying the three-dimensional approach to improve or establish forest energy supply chains in the future.

The evaluation of the **technical dimension** of the supply chains, demonstrated the importance of in-depth knowledge about each step in the supply chain since minor modifications at the supply chain links can have a great effect on the overall operational efficiency. The study, as well existing literature, demonstrated that natural drying, partial debarking, covering, and proper pile establishment and location can contribute to a more efficient drying of raw material in the forest. Furthermore, the transportation of biomass is subsequently more efficient since more biomass and less water is transported. At the chipping stage, it was demonstrated that the operational environment has a large effect on chipping productivity. The study has given several recommendations on how chipping productivity can be improved with very limited modifications to existing working methods, thereby increasing overall chipping capacity in the operational environment.

On the **social level**, the organizational framework of forest fuel supply was analyzed. The study revealed the effect of the operational environment on the organizational setup of the supply chain. Furthermore, several obstacles to a more efficient way of working were found, and solutions on how to overcome them were presented. For instance, in order to overcome some of the strong working traditions that hamper efficient supply structures, it will be necessary to apply a holistic planning approach and to implement new business models that are independent of existing traditions and working methods. This would allow for a significant overall change in the supply structure and improvement of biomass supply.

Finally, on an **economic level**, the thesis demonstrated the importance an economic analysis prior to establishing supply chains in a new operational environment. It was revealed that forest biomass for energy can be a viable option for energy production in the Scottish Highlands. This can be achieved by adapting the existing supply structures taking into account the different operational environment in Scotland. The study demonstrated that simple technology transfer is not enough to be successful. Real success can rather be achieved by combining the technology and knowhow to be transferred with existing expertise, thereby creating new innovative knowledge and solutions. The thesis has revealed several solutions to improve the operational efficiency on all three complexity levels and highlighted some of the obstacles that have to be overcome in order to establish long lasting efficient supply chains in different operational environments.

The ambitious targets and efforts to combat climate change will be challenging to meet by the global community. It is clear that the use of forest biomass for energy to meet the targets will play an important role in many countries. The uptake of new technological innovations and development usually takes many years. Therefore, in order to meet the targets, it will be necessary to rely on existing technology and methods to produce forest biomass for energy. At the same time, it will be necessary to invest into new machinery in order to increase harvesting volumes. However, another path to move ahead is to increase the efficiency and productivity of existing operations and supply chains by applying the presented three-dimensional approach in order to meet the growing demand in the future. This, in return, will decrease the overall costs and limit the necessary investments into new machinery and equipment, thereby bringing the global community one step closer to achieving its ambitious climate change targets.

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