Dissertationes Forestales 189

Process redesign in development of forest biomass supply for energy

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Academic dissertation

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ABSTRACT

Wood plays an important role in the production of renewable energy in the EU which is going to grow further in the future. The economics of operations, however, are still critical. The aim of the present thesis was to investigate the potential of process improvement measures to increase the performance of biomass to energy supply operations.

Article I and II investigated the organizational structure and business process for forest biomass procurement of a German integrated roundwood and energy wood procurement chain by means of business process mapping. The business process was then analyzed and redesigned by the method of business process reengineering. Furthermore, two new business processes were developed which are to be applied in procurement operations only for energy wood. Article III analyzed the raw material allocation process currently in use by supply chains from roadside storage to plant in the Finnish region of North Karelia. It developed an alternative, information-based process using data on the transportation distance, drying models for forecasting the moisture content and data on the volume of the storages. Discrete-event simulation was used to compare current and new processes and to analyze their effects on the economics of operations. Article VI investigated the cost-saving potential of improving data management and information logistics through the application of information and communication technology. Its profitability was analyzed by a cost-benefit analysis.

The economic analysis of the business process reengineering showed that the reengineered To-be process can potentially cut costs by up to 39% relative to the currently applied business process. The information-based raw material allocation process could the energy content delivered by the supply chain by up to 9% over the entire year and by up to 29% during the peak period in winter when the fuel demand of the plant is highest. Applying ICT in to investigated cases in Finland showed a net present value of 212 739 € over a time span of ten years at an annual production of 150 000 loose-m^3 in the first case. In the second case the net present value was even 969 841 € which seemed to be very high at an annual production of 37 000 loose m^3.

This thesis demonstrates that process improvement can considerably increase the productivity and cost-efficiency of existing forest biomass supply chains.

Keywords: supply chain management, discrete-event simulation, process improvement, forest fuel

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Joensuu, January 2015

Johannes Windisch

LIST OF ORIGINAL ARTICLES

This dissertation consists of a summary and the four following articles, which are referred to by roman numerals I-IV. Articles I, II and IV are reprints of previously published articles reprinted with the permission of the publisher. Article III is the authors' version of the submitted manuscript.

I Windisch J., Röser D., Mola-Yudego B., Sikanen L., Asikainen A. (2013). Business process mapping and discrete-event simulation of two forest biomass supply chains. Biomass & Bioenergy 56: 370-381.
doi: 10.1016/j.biombioe.2013.05.022

II Windisch J., Röser D., Sikanen L., Routa J. (2013). Reenegineering business processes to improve an integrated roundwood and energywood procurement chain. International Journal of Forest Engineering 24(3): 233-248.
doi: 10.1080/14942119.2013.857833

III Windisch J., Väätäinen K., Anttila P., Nivala M., Laitila J., Asikainen A., Sikanen L. (2014). Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain. Manuscript.

IV Windisch J., Sikanen L., Röser D., Gritten D. (2010). Supply chain management applications – cost or benefit? Silva Fennica 44(5): 848-858.
doi: 10.14214/sf.124

Johannes Windisch had the main responsibility in regard to the entire work done in article II and VI. Mikko Nivala did the GIS analysis, Perttu Anttila helped with the indexing system, Lauri Sikanen and Johanna Routa with the data collection. In Article I the author and Dominik Röser shared responsibility for the design of the study, method selection, data analysis, interpretation of results and writing of the article. The author was responsible, in addition, for the data collection and calculations. Finally, in article III, the author and Kari Väätäinen shared responsibility for the method selection, study design, data analysis, interpretation of results and writing of the article. Kari Väätäinen was responsible for data collection, the author for data preparation and development of the simulation model. The co-authors improved their respective article by commenting on the study setup and the manuscript.

CONTENTS

1 INTRODUCTION

1.1 Forest biomass for energy in the EU

Renewable energy is high on the agenda of climate and energy policy in the European Union and worldwide. The mitigation of climate change is the most perceived reason for this development. However, in the coming years and decades the European Union must tackle energy related problems beyond CO_2 emissions and climate change. The EU imports a large share of its energy demands from a few countries, mainly in the form of fossil fuels, the prices of which have increased considerably over the past decade (CEC 2006a). This energy dependency is going to increase in the future if no measures to increase the domestic energy supply are undertaken. For these reasons, finding domestic sources of energy to cover the energy demand is a challenge the EU is facing (CEC 2006b). The important role that forest bioenergy is going to play becomes evident in numerous policy measures from the European Commission. Already in the Biomass Action Plan (CEC 2005) the European Commission emphasized the important role of forest biomass. Consequently, one of the key actions in the Forest Action Plan for the period from 2006 to 2011was to “promote the use of forest biomass for energy generation” (CEC 2006c).The essence of these Communications can be found in a Directive of the European Parliament and Council setting targets about the implementation and use of bioenergy in its member states and not least naming figures for the share of bioenergy in the overall energy mix of each country for the year 2020 (Official Journal of the European Union 2009), calling for an average of 20% renewables in the energy mix of the member states. In 2011 energy from wood and wood waste provided a share of 47.8% of the total consumption of renewable energies in the EU (European Biomass Association 2013).For meeting the requirements of the EU, consumption of wood for energy is expected to increase from 346 million m^3 in 2010 to 573 million m^3 in 2020. Following this development in 2030 the demand might even reach 752 million m^3 (Steierer 2010). Verkerk et al (2010) estimated the realistic supply of forest biomass at a range from 625 to 898 million m^3, which supports the earlier result of Asikainen et al (2007). As these figures involve also roundwood for material use, this development poses a problem for European forestry. Firstly, the demand for wood for energy is going to exceed the demand for wood for material uses from 2020 onwards, meaning a structural change of the wood market (Mantau and Saal 2010). Secondly, considering that the demand for wood for material use is going to increase as well, the wood demand is going to exceed the supply potential between 2015 and 2025 (Mantau 2010).Recently, the European Union has revoked the binding targets for the member states but stressed the importance of and emphasis on renewable energies in the energy mix of the EU in the future (CEC 2014). Locally, forest biomass offers a remarkable source of renewable energy in many European regions, and forest science must find solutions to how supply and demand can be balanced. The greatest challenge is closing the gap between the theoretical potential and the technically and economically available in order to ensure a sustainable wood supply.

1.2 Forest biomass supply chains

The Nordic countries, in particular Finland and Sweden, have a comparatively long tradition in forest energy and they are considered to be forerunners in this field of forest business (Routa et al 2013). Like few other countries, they produce a large share of their renewable energy from wood (Mantau and Saal 2010) and consequently utilize a considerable share of their biomass potential already (Alakangas et al 2007, Asikainen 2007). However, due to high costs and low product value the economy of forest biomass procurement is critical. In Finland the cheapest source for wood fuel, residues from the timber processing industry, has been utilized to the full extent for years and consequently energy wood resources have to be exploited to broaden the raw material base (Hakkila 2004). Economically the most uncritical energy wood assortment is logging residues. Nowadays, they are procured in integrated logging operations for procuring industrial roundwood and energy wood where the higher value roundwood assortments bear the cost of operations and logging residues are the side product (Ryymin et al 2008, Laitila et al 2010a). Biomass from whole-trees from precommercial thinnings, in contrast, is more costly to procure. In addition to transport and comminution logging costs apply (Laitila et al 2010b). Such operations were subject to studies which demonstrate how sensitive their economics are. For example, Ahtikoski et al (2008) found that changes of the logging costs of only ± 15% have a significant effect on the profitability of such operations.

Different wood assortments and versatile operational environments, in practice, require a variety of different supply chain setups (Figure 1). In general, the forest biomass supply chain can be broken down into five basic steps: Purchase of stands, logging, forwarding, chipping, transportation and storage, which may happen in different phases of the operation, depending on the setup of the supply chain. Supply chains from roadside storages to plant comminution and transportation are the critical cost factors (Laitila 2010b). In contrast to other resources, wood is scattered over large areas, which requires efficient logistics. Trucks are the dominant option for transportation (Kärhä 2011). Transportation by train (Tahvanainen and Anttila 2011) and waterway (Karttunen et al 2012) can be the most cost-efficient alternative for large-scale CHP plants with large supply radii.

Designing supply chains and entire networks is a challenging logistical problem where many factors must be taken into considerations (Gronald and Rauch 2007). A key decision factor for the supply chain setup is at which location the comminution is to happen (Figure 1). The setup that allows for the highest chipper utilization is centralized comminution at terminals or the end-use facilities. However, the bulk density of uncomminuted material is only about half of the one of wood chips (Angus-Hankin et al 1995) and causes high transportation costs (Ranta and Rinne 2006) allowing only short transportation distances. Furthermore, for such a setup to work economically, full employment of the expensive machinery and large annual volumes to be processed are required (Asikainen et al 2001). Finding suitable locations for terminals is challenging with regard to transportation distance, amount of available space and legal restrictions, for example due to noise protection near residential areas. Terminals increase the security of supply but, simultaneously, increase the costs of operations (Gronald and Rauch 2010).

In Finland the most common forest biomass supply chain from roadside to plant is made up by a mobile chipper and 2 to 3 chip trucks (Ranta 2002, Asikainen 2010, Laitila 2012, Routa et al 2013). The energy wood is chipped at the roadside straight onto the trucks. Currently, 75% of logging residues and 68% of energy wood from precommercial thinnings are processed this way (Strandström 2013). The direct chipping onto trucks is called a “hot chain” where the machines are dependent on each other. That means both chipper and truck must be present at the roadside storage to be able to work, which causes idling times for both machines (Asikainen 1995, Spinneli and Visser 2009, Zamora-Cristales et al 2013, Eriksson et al 2014).

A well balanced machinery setup is required to keep these idling times low and operations economical. Eriksson et al (2014) investigated different supply chain setups for stump fuel in Sweden. Their results show a large difference in system costs. For the shortest transportation distance of 25 km, system costs varied from 32 € to 60 € per oven dry tonne (odt), while at a

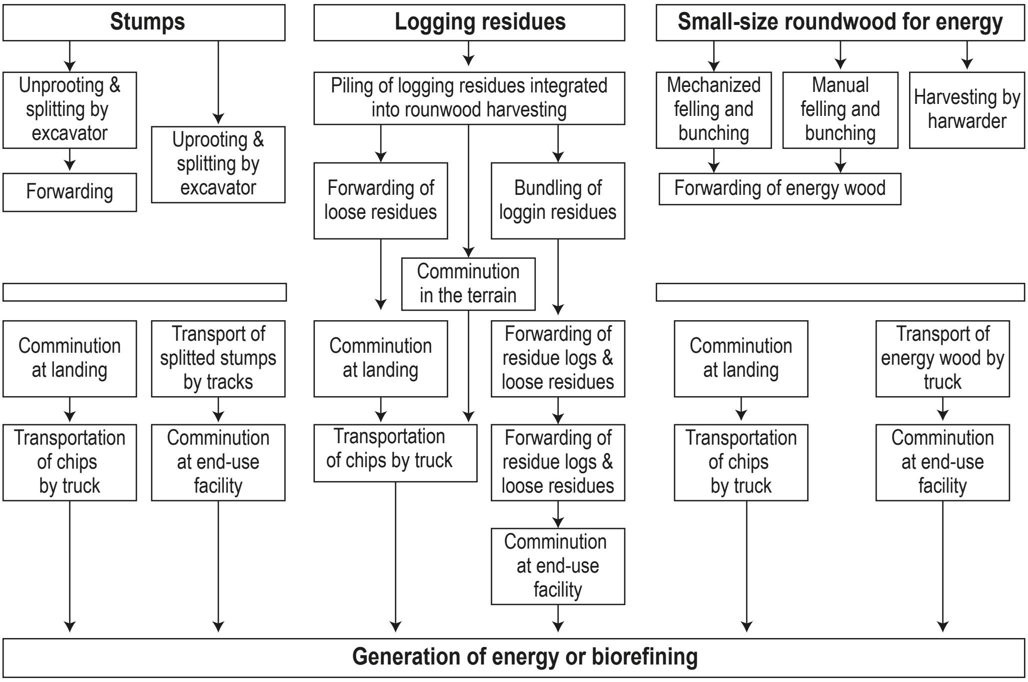


Figure 1. Overview of different setups of forest biomass supply chains dependent on the raw material (Laitila 2006 edited by the author).

transportation distance of 150 km an even larger variance of 52 to 105 € per odt was found. Idling times of the grinder were an important cost-factor and setups which caused long idling times were not competitive. Zamora-Cristales et al (2013) found similar results where the overall costs of the supply chain are directly linked to the idling time of the chipper. In their study, low round-trip distances of up to approximately 70 km using 2 single-trailer trucks was the most cost-efficient option. At distances between about 80 and 220 km, 2 double trailer trucks were required to keep the idling time of the chipper low, making for the best cost-efficiency. At distances between about 220 to 280 km 3 double trailer trucks were required. These results demonstrate the importance of the right machine setup, in particular regarding transport capacities, in forest biomass supply chains and the effect of machine interactions on the economy in hot supply chains.

Organizing and managing forest supply chains are demanding tasks. The multitude of decisions which has to be on a company and cross-company level was discussed by Weintraub and Epstein (2002). They point out the weakness of some links between components of the supply chain, in particular in terms of “transmission of information and coordination of decisions” (Weintraub and Epstein 2003 p. 358). That applies especially to forest biomass supply chains. In particular, the large number of actors and stakeholders (Eberhardinger 2009, Röser 2012, Routa et al 2013) poses a challenge regarding the organization and coordination of operations. While in large-scale supply chains run by big forest enterprises the use of ICT for coordinating operations is common practice, small and medium-scaled supply chains still largely rely on phone and paper documents for exchanging information (Seppänen et al 2008, Röser 2012), a method that is inefficient and prone to errors (Bauer 2006) and thus costly.

In Sweden the procurement costs of forest biomass have decreased significantly within the past 30 years (Junginger et al 2005). It can be assumed that a similar development has been taking place in other countries and is going to continue in a similar fashion during the coming years. Especially as the research and development is unlikely to stop what becomes evident by having a look at recent developments and inventions in equipment for forest biomass procurement (Thorsén et al 2011, Routa et al 2013). Besides the development of new machinery, the improvement of organization, management and decision making holds promising potentials for improving the cost-efficiency of operations.

1.3 Quality issues

Fuel quality is an important factor for the economy of forest biomass supply chains. Impurities, such as rocks and soil, damage chippers and feeding systems and increase the ash content of the material. Inappropriate handling of the energy wood, in particular in forwarding, may cause contamination of the raw material. However, soil and rocks can be introduced into the roadside storages as well, for example through snow blowing in winter (Asztemborski al 2013). Stump chips in particular are subject to contamination. Laitila and Nuutinen (2014) found up to 12.2% of the comminuted volume to be impurities.

However, the most important quality factor is the moisture content (Asikainen 2001, Röser et al 2011, Acuna et al 2012). High moisture content decreases the calorific value of the raw material (Hakkila 1978, Nurmi 1993, Flyktman and Helynen 2004, Alakangas 2005). In addition, high moisture content decrease the energy density of the biomass what prohibits the utilization of the full loading capacity of chip trucks due to limitations of the maximum pay load. During the storing of the energy wood and wood chips, high moisture contents have a negative effect on the storing properties of the material resulting in elevated microbial activity, which causes dry matter losses (Dix and Webster 1995).

Earlier studies showed that the drying behavior of energy wood storages largely depends on spatial location and storage conditions (Nurmi 1999, Röser et al 2011), in particular climate conditions at the storage location, ventilation and exposure to the sun (Nurmi 2007). The climate conditions also lead to significant seasonal variation of the moisture content (Nurmi and Hillebrand 2007, Sikanen et al 2013). Therefore, earlier studies demanded to utilize the knowledge gained from drying trials for a better timing of operations (Petterson and Nordfjell 2007, Gautam et al 2012).

Not only is the moisture content of the raw material subject to seasonal variations, but the demand for heat energy also varies over the year. While in summer the heat demand is relatively low, it firmly peaks in winter (Anderson et al 2002). Therefore, it is desirable to supply energy wood with high calorific value during peak periods to maximize the energy output. Meeting this aim requires the ability to predict the drying behavior of energy wood storages. Then the right material can be supplied at the right time, meaning sound decisions can be made on which storages should be processed in certain seasons. In recent years, research aimed to develop drying models for different energy wood assortments so that their moisture content can be forecasted. Filbakk et al (2011) developed drying models for bundled and loose logging residues in Norway and the effect of various variables on the drying. Erber et al (2012) developed a similar model for pine roundwood for energy in Austria. The economic analysis of the model shows that within a year the increase of calorific value of the wood resulted in an economical benefit of 14.40 €/air dry tonne. According to Erber et al (2012) simple and cost saving input required for using such models in practice. Therefore, their model uses the variables wind speed, air temperature, precipitation and relative humidity. Averages for these variables can be easily obtained from weather records. By means of heuristic fitting, Sikanen et al (2013) developed drying curves for logging residues for Central Finnish conditions. They are meant to be easily implementable in bioenergy enterprise resource planning software. Solving the problems related to quality of energy wood and wood chips became an important field of research in recent years. Considering the competition for forest biomass, it is desirable to maximize the energy generation, and thus the benefit. The potential lying with improved quality was demonstrated by Acuna et al (2012). They used the drying curves by Sikanen et al (2013) to optimize the logistics of a Finnish biomass supply network by linear programming. The study demonstrated that proper drying can increase the calorific value of the energy wood by 33% and thus reduce the fuel consumption of the focal plant in terms of volume by the same percentage.

1.4 Process improvement in wood procurement chains

The presence of efficient and productive equipment is crucial for high productivity. However, besides that, the machinery and interdependencies between different elements of the supply system must be well balanced to provide for high efficiency (Asikainen 1995). One example which proves that point is the scheduling of trucks for chipping operations at the roadside storages. Spinelli and Visser (2009) and Röser et al (2012) found out that most delays in such operations are operational delays, meaning no trucks are present, causing the chipper to stand still. This shows the need for improving operational management.

Wood procurement chains, however, not only consist of machinery. Operations must be organized and managed, which involves a considerable work effort for all actors (Röser 2012). Depending on the operational environment, the procurement processes have different setups which pose considerable cost factors and leave room for improvement (Gronalt and Rauch 2005, Röser 2012). Wood procurement chains must take into account that, besides having productive machinery in place, a crucial factor for productivity and efficiency is having efficient business processes in place. Röser (2012) found that in forest biomass procurement chains, reengineering business processes is necessary to take a leap towards increasing operational efficiency. Forest biomass is a rather young branch of forestry, and supply chains are still immature, in particular on a small and medium scale. The business processes for organizing and managing the operations are often copied from the roundwood business, meaning they may not be fully adapted and thus of low efficiency (Röser 2012).

The method of business process reengineering (BPR) has enjoyed great popularity since Hammer (1990) published his highly influential article “Reengineering Work: Don’t Automate, Obliterate”. In this article he urges the reader to rethink the ways in which work is organized. As business processes take on various forms and can be performed innumerous ways, different approaches can be taken towards BPR.

While in the early days of BPR leading researchers in the field were convinced that it is a creative process based on imagination and experience (Hammer 1990, Hammer and Champy 1993), later researches put a more methodological view on the topic (Melão and Pidd 2000). Numerous guidelines, frameworks and tutorials were published. Grover and Malhotra (1997) give an overview what stages BPR should involve and assess reasons for failures. They point out that, among others, creating and understanding of the process, for example by means of process mapping, facilitates the diagnosis of problems and opportunities. This stage is followed by process creation with the aim of identifying alternative implementations or completely redesigning the process.

In small and medium-sized forest biomass procurement chains, business processes in practice are often not designed but developed from traditions and based on personal contact and interaction between the stakeholders (Röser 2012). Under such circumstances, defining the actual business processes is a critical task for reengineering. Melaõ and Pidd (2000) provided an extensive framework of different perspectives which can be applied to business processes, and facilitate their understanding, modelling and improvement. Among others, business processes can be defined as complex dynamic systems with inputs, outputs, boundaries and transformations. Nonetheless, they are social constructs defined by interpretation of the individuals involved. The interpretations again are defined by beliefs, values, previous experiences and expectations. Furthermore, the individuals may follow different agendas. In contrast to the social issues mentioned by Grover and Malhotra (1997), in forest biomass supply chains, frequent problems are related to lack of trust among the numerous stakeholders and companies and conflicts of interest between for example the forest owner, the machine contractors and the forest service providers and must not be ignored (Röser 2012). Reijers and Mansar (2005) described various BPR frameworks provided an overview of 29 proven best practices for streamlining business processes and when and how to apply them.

Grover and Malhotra (1997) define the “nucleus of reengineering” by the following four elements:

1. It consists of radical or at least significant change.
2. The unit of the analysis is the business process as opposed to departments or functional areas.
3. It tries to achieve major goals or dramatic performance improvements.
4. Information technology (IT) is a critical enabler of this change.

Like Hammer (1990) they advertised a dramatic improvement that can and should be achieved through business process reengineering. Other studies on this matter emphasized that a more cautious approach may be less prone to failures while still leading to considerable improvements. Chan and Choi (1997) pointed out that expectations of BPR are frequently set too optimistic and not achieving them leads to abandoning the project. The problem of setting too optimistic targets is often paired with a lack of recognition of benefits (Chan and Choi 1997). This issue may become critical in particular when cross-company processes are reengineered and not all participating company leaders can be convinced due to a lack of visibility of benefits (Eberhardinger 2009). A thorough economic analysis of the expected outcomes, for example by simulation, is a possible solution to these issues as it makes potential risks and benefits visible before implementation of reengineered business processes and is suggested as a tool for putting BPR on a more scientific basis (Melão and Pidd 2000, Su et al 2010).

In contrast to the findings of Melão and Pidd (2000), small and medium scaled enterprises use very flexible BPR approaches (McAdam 2002) as are favored by earlier studies (Hammer 1990, Hammer and Champy 1993, Grover and Malhotra 1997). In forest technology research this approach is popular, too. Undoubtedly, IT or rather information and communication technology (ICT) are a crucial factor for efficient business processes. It saves time, removes human errors and increases the accuracy of the data exchange (Gunasekaran and Nath 1997). ICT is applied for improving the so called information logistics. There is no universal definition for the term information logistics yet (Haftor 2012). However, its goal can be described as enabling “the effective and efficient delivery of needed information in the right format, granularity, and quality, at the right place, at the right point in time, to the right actors" (Michelberger et al 2013). Consequently, ICT has found its way into forest business in various forms and plays an important role in BPR. Large forest enterprises use supply chain management (SCM) and fleet management (FM) applications in their operations and have achieved considerable benefits (Linnainmaa et al 1996). As SCM and FM applications became available for small and medium-scale supply chains the use of BPR and ICT were recognized as means to improve the efficiency of their operations, too (Sikanen et al 2005).

Earlier studies used BPR to improve the intra-organizational processes for industrial roundwood operations. Hug (2004) reengineered the wood procurement business processes of a state forest district in Southwest Germany using ICT. Besides the improvement potential through the use of ICT, other studies found the need for improving the organizational structure in forest owners associations and for the professionalization of staff (Bauer 2006, Baumann 2008).

Lemm et al (2006), in a case study, improved the storage management and delivery logistics management by applying ICT to an industrial roundwood supply chain from roadside storage to customer in Switzerland. The benefits gained by the actors in the supply chain amounted to about 117 300 € per year (73 000 m^3).

Hammer (1990) and Grover and Malhotra (1997) criticize that changes in BPR projects are made primarily through ICT. This practice neglects the principal of actually making a business process more efficient and rather accelerates an inefficient process through computerization. Major improvement can be made by focusing on organizational structure, people and jobs in business processes and skills required for them. Essentially that means: Rethink the process first, then use ICT to implement and accelerate it. Therefore, ICT is to act rather as an enabler than a leader in BPR (Grover and Malhotra 1997).

An example in a forestry context was found by Bodelschwingh (2006). His study revealed that companies involved in wood procurement often act like stand-alone actors. The idea of integrating cross-company business processes to form a tightly linked supply chain and utilize arising synergy potentials is implemented rarely in small and medium scaled procurement operations. Bodelschwingh (2006) addressed this problem by using BPR to implement supply chain thinking in a German forest procurement system and then applied ICT as an enabler. By this approach the pass-through time of the timber could be reduced by 28% and the costs by 4 to 7 €/m^3.The importance of these results becomes evident when comparing them with availability studies. Torén et al (2011) studied the availability of forest fuel from logging residues in the Finnish region of North Karelia in the year 2030 depending on the procurement costs. According to their results, a decrease in procurement costs of 3 € per m^3 would triple the economically available volume.

1.5 Research problems

The utilization of forest biomass has been increasing and is going to continue to increase, according to recent research (Mantau 2010). The economy of operations is critical and will be even more so in the future, when more and more economically unfavorable resources will have to be tapped to keep up with demand. Undoubtedly, further investments into the development of technology and infrastructure will be required for finding solutions to these problems (Routa et al 2013). However, highly productive machinery is in place already and the productivity per effective machine work hour (E_0h) of the single machines has reached a level where further increments are hard to achieve.

The cost efficiency of supply chains depends not only on the productivity of machines. Supporting processes must be established which allow to make use of the potential productivity, more precisely, efficient organization and management. There are research problems related to that:

1. The business process related to organization and management of the supply chain is complex and leaves room for improvement. However, the costs related to that are not exactly known. In general, the organization and management of forest biomass supply chains was largely a black box before Röser's study (2012). It is to be investigated how such a process can be reengineered and which saving potentials lie with streamlining business processes.
2. The allocation of raw materials is a difficult task, in particular under consideration of the seasonal variation of the fuel demand of the plants. The main factors influencing the economy and productivity of operations are the transportation distance and moisture content. Drying models were developed which facilitate forecasting of the moisture content so that the calorific value of the delivered material can be increased. However, it is not known to which extend these factors are considered in the decision making of the current raw material allocation process. The research question here is: what is the potential benefit of a raw material allocation process based on this information and what are its effects on the logistics and related costs of the supply chain.
3. The management of forest biomass operations is data and communication intensive. Data management and information logistics are time-consuming activities and prone to error if not done properly. ICT for supply chain management is available on the market but not widely used in small and medium-scale operations. Reason for that is the actors' resistance to change and their reluctance to invest in these technologies without knowing their potential benefits.

These research problems translate into the framework of the thesis which is presented in Figure 2.

1.6 Aim of the thesis

The primary aim of the this thesis is to test the potential of methodologies of process improvement to increase the performance of forest biomass supply chains by streamlining business processes, increasing the use of precise data and improving information logistics. The aim can be divided into three research questions:

1. What costs are related to organization and management of operations and can business process reengineering help to increase the cost-efficiency of operations?
2. What is the current raw material allocation process in forest biomass supply chains and how does raw material allocation based on information on moisture content, transportation distance and storage volume affect the performance of the supply chain?
3. What is the cost-benefit ratio of implementing ICT-based supply chain management applications for data management and information logistics in forest biomass supply?

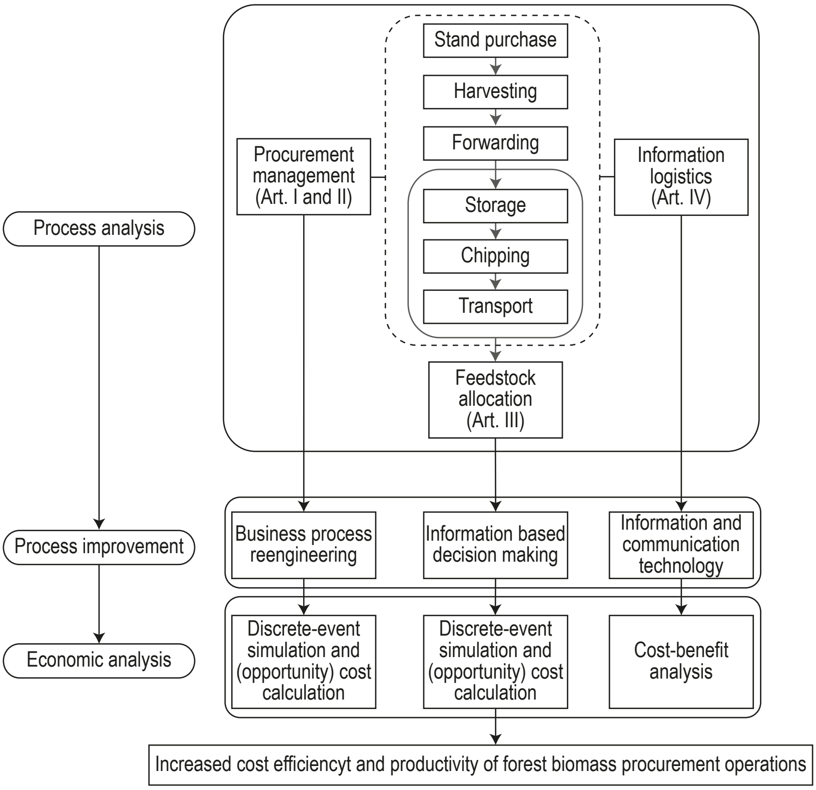


Figure 2. Framework of the thesis: Three processes involving different elements of the procurement chain were analyzed. In the second step, methods for process improvement were applied. Finally, the economics of the suggested improvements were analyzed and compared to the status quo.

2 MATERIAL AND METHODS

2.1 Reengineering of the biomass procurement process

2.1.1 Description of cases

In a case study a medium scale forest biomass supply chain was investigated. It is located in the South of Germany, in the municipality Feldkirchen-Westerham (FELD) and supplies a 1.5 MW district heating plant in the nearby municipality of Glonn. MW Biomass, the cooperative running the plant, is an affiliate company of the local forest owners association (FOA) who is one of the main suppliers of the plant. In general, forest operations solely for energy wood procurement from pre-commercial thinnings are not common in Germany (unlike in Finland). Therefore, raw materials for forest fuel are mainly 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 contractors. The average removal per logging site is 150 solid-m^3. The biomass is regarded as a by-product, and depending on the logging site it makes up roughly 10% of the overall removal. Concerning the calculations, there is no distinction between assortments of merchantable roundwood and logging residues.

2.1.2 Mapping and analysis of the as-is processes

By expert interviews the data for the business process mapping were gathered. The interviews followed a detailed sequence of open questions. First, the task of the actor was outlined. Then the activities involved in them, including the interactions, dependencies and contact points with other stakeholders, were discussed. Finally, points and methods of communication and data exchange and sources of conflicts and errors were analyzed. After the maps were drafted using Sigmaflow® software, they were evaluated, refined and developed further in subsequent meetings with the interviewees, who were key actors in the supply chain (Table 1), until no further improvement could be made. The information given by the different stakeholders was cross-checked to verify that the resulting interactions were matched with each other.

Table 1 Key actors interviewed for the business process mapping

FELD
Logging Contractor
FOA Operations Supervisor
FOA Accounting Office
Chipping Contractor
MWB Sales Manager
MWB Logistics Manager

The data gathered during the interviews was processed using basic techniques of business process mapping (Damileo 1996). Besides the sequence of activities, the communication and data exchange between functional units and payment processes were included (Table 2). Sigmaflow® mapper facilitates drawing and handling even comprehensive process maps.

Table 2. Nomenclature of process objects used in the business process mapping.

Type	Object	Description
Activities	*Payment*	Transfer of money between functional units
	Communication	Exchange of data and paper documents by means of emails, phone calls, oral conversations, postings
	Action	Action are performed to fulfil sub tasks in the process such as creating maps, evaluating stands, moving between work sites etc.
Information 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 the 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
Actor		A company, institution or other stakeholders in the process. Can be made up of several functional units or act as standalone functional unit.
Functional unit		E.g. an operations supervisor or logging contractor. Carries out activities in the process to fulfil a specific task in the supply chain.

The process maps and analysis are the result of paper I. They are the basis for reengineering of the business process. For this reason, the results are presented in the Material and Methods chapter of this thesis.

Structure of the business processes

The setup of the supply chain and the actors and functional units (Table 3) involved are typical for Bavarian working environments. An actor in the supply chain can be: an institution, company or stakeholder involved in the supply chain. A functional unit by contrast carries out specific tasks. Therefore, a functional unit may consist of several functional units or act as a standalone functional unit.

Table 3. Grouping of functional units within the supply chain.

Group	Actor	Functional unit	Acronym
Forest owner	Forest Owner	Forest Owner	FO
Forest authority	Forest Authority	Forest Authority	FA
Forest service provider	Forest Owners Association	FOA Operations Supervisor	FOA OS
		FOA Accounting Office	FOA AO
	Timber Broker	Timber Broker	TB
Contractors	Logging Contractor	Logging Contractor	LC
	Chipping Contractor	Chipping Contractor	CC
	Hauling Contractor	Hauling Contractor	HC
Plant	MW Biomasse	MWB Logistics Manager	MWB LM
		MWB Sales Manager	MWB SM
		MWB Plant Manager	MWB PM
		MWB Accounting Office	MWB AO

FELD consists of 8 actors and 12 functional units. An overview of the sub-processes is given in Figure 3. In the maps the actors are grouped to lower the complexity (Table 3): Functional units providing services to the forest owner are grouped under forest service providers (FSP). One group represents the contractors (CON) and another one the functional units of the actors running the plant (PLA).

The business process mapping revealed 183 activities involved in the procurement process and a total of 268 process objects.

Business process modelling

The basis of the business process reengineering was the As-is process of the German industrial roundwood and energy wood procurement chain. Three processes were developed using different approaches with the aim of lowering the costs of wood procurement. Firstly, the existing integrated process was reengineered using a creative process as suggested by McAdam (2002), largely based on the best practices for BPR presented by Reijers and Mansar (2005). In contrast to the radical clean-slate approach suggested by Hammer (1990), the modelling of the To-be process was oriented toward the existing As-is process. Existing traditions play an important role in forest biomass procurement (Röser 2012). Taking this into account avoids creating an apparently effective but unrealistic process which would be impossible to implement in the existing framework (Chan and Choi (1997). The following best practices were used:

- Empowerment: Functional Units (FUs, Table 1), in particular the contractors, are empowered to make decisions on their own without being constantly supervised by other FUs.
- Task elimination: The business process is examined carefully to identify and eliminate unnecessary and redundant tasks.

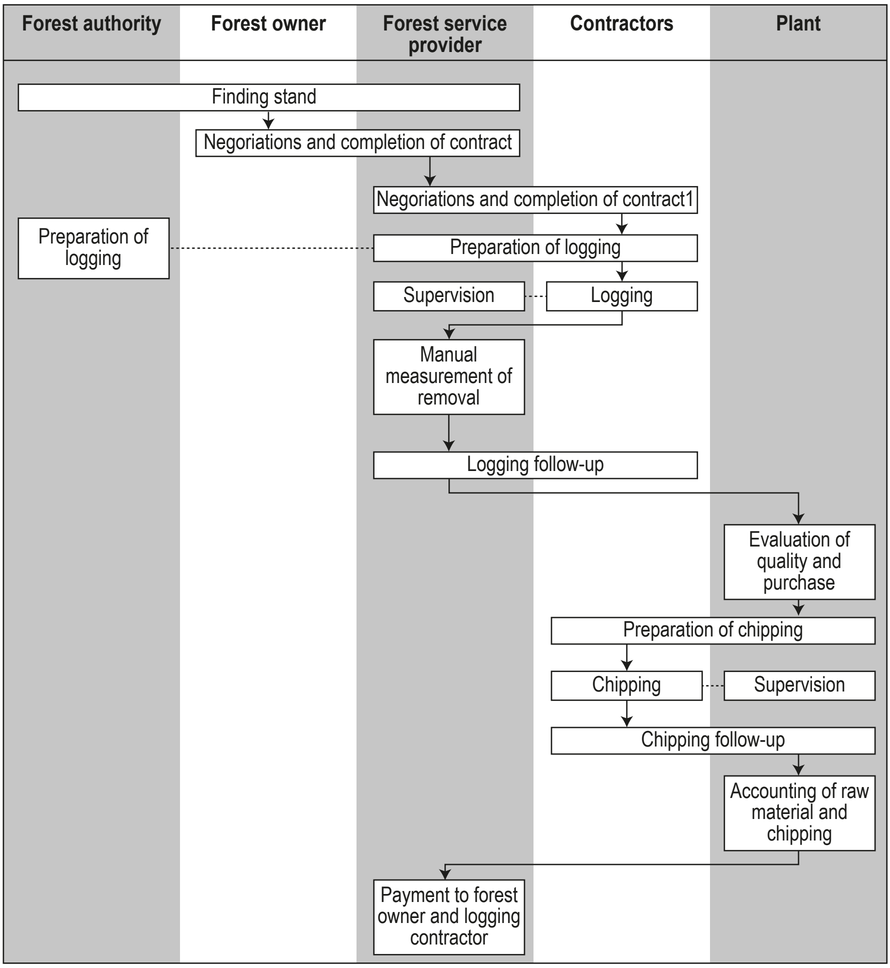


Figure 3. Map of the sub-processes involved in the procurement process.

- Numerical involvement: The number of FUs involved in the business process is reduced as much as possible.
- Contact reduction: Contacts between FUs are reduced to a minimum.
- Standardize data collection: A data collection standard is introduced for use in all parts of the procurement chain.
- Digitalize data exchange: To ensure immediate usability of data, avoid loss of data and simplify storing, the data exchange is digitalized.

In the second approach two business processes were developed which are to be applied solely for the procurement of biomass from precommercial thinnings. The preconditions for these business processes are presented in Table 4. The results of the business process modelling are presented in the form of process maps with grouping of actors as described in Table 3.

Table 4. Preconditions for the Biomass and Biomass FA business process models.

Biomass	Biomass FA
LC capable of laying out skid trails and selecting trees independently	District forester of the FA is reliable and capable of supervising logging operations
Maximum purchasing price for biomass is known	Forest Owner and stand, respectively, are eligible for subsidies
All FUs are reliable and capable of fulfilling their tasks properly and independently	
Forest Owner does not demand joint stand visits	

2.1.3 Discrete-event simulation modelling

Model structure

The sequence of activities in a process is relatively complex and influenced by various decisions and events occurring over time. It constitutes a dynamic discrete system (Banks et al 2010). Sigmaflow Modeller® facilitates building discrete-event simulation models based on process maps drawn with the Sigmaflow Mapper®. Based on the process object types *activities, others* and *functional units* (Table 2) a number of object oriented discrete-event simulation models were built for determining the organizational an managerial work load (OMWL). OMWL includes all activities that are related to the organization and management of the procurement chain and the operations. It is given in min/m^3.

Discrete-event simulation is based on randomness of events. For creating randomness the simulation models employ random numbers which are generated based on mathematical distributions to describe the variation of the time consumption of each activity. Depending on the type of activity, different distributions were employed. For Communication activities, such as phone calls and face-to-face conversations, a left-skewed Erlang distribution with a shape parameter $k = 3$ was chosen (Gans et al 2003), as Sigmaflow Modeler® does not provide log-normal distributions. Time to complete a task is often normally distributed (Banks et al 2010). Therefore, all other activities used normal distributions with a standard deviation of ±25%, because in practice the time consumption of different activities will vary over a wide range. Besides the model for the whole procurement chain, the limitations of Sigmaflow® made it necessary to build a separate model for each functional unit, resulting in a total number of 13 models for the As-is business process. Each model was run 30 times with different random number streams. Per run 30–35 transactions were simulated.

For the newly designed business processes 10 simulation models were built for each new business process model. Five different scenarios regarding the probabilities of failures were assumed: 100%, 75%, 50%, 25% and 0%. For example, in the scenario "100%" in all transactions failures occur while in the scenario "0%" no failures occur. Failures in these cases mean that problems occur resulting in additional activities which are undertaken to solve the problem and require additional work input from one or several functional units. Each model was run five times using different random number streams. About 30 transactions were simulated per run.

The model was validated by running it step by step and checking whether the elements of the model behave logically. Then the results of the OMWL per FU of the As-is business process were double checked by experts working in the supply chain, and found to be realistic.

Input data

The input data for the models are expert estimations on the mean time consumption of each activity. A panel of experts from the Finnish Forest Research Institute was employed who have been working in the field of forest biomass procurement in both countries.

2.1.4 Economic analysis

A holistic cost calculation including all actors and stakeholders was conducted to compare the different business process models and scenarios regarding the costs related to the OMWL. Key figures on production and costs (Table 5, Table 6) were identified and obtained from the supply chain which supplied 93 560 solid m^3 of industrial roundwood and 3 555 solid m^3 of energy wood in this year. In the case of the service providers and the forest authority, hourly staff costs, mileage allowances and, when applicable, commissions were applied. Given that the machine contractors are not able to run their machines while carrying out organizational and managerial tasks, opportunity costs accrued. Because the contractors were not able to provide data regarding machine productivity and costs, exemplary calculations were made.

Table 5. Operational costs and productivity figures for the machinery involved in the supply operations.

Variable	Value
Operational costs (€ m^{-3})	
Harvesting	10.5
Forwarding	5.5
Chipping	7.5
Transport	7.5
Productivity figures	
Average harvester productivity (m^3 PMH^{-1})	9.70
Average volume per logging operation (m^3)	150
Average volume per chipping operation (m^3)	~125
Average chipper productivity (m^3 PMH^{-1})	28

Table 6. Staff costs of the functional units and related cost factors (Acronyms are defined in Table 3).

Variable	**Value**
Staff costs	
FA (€ h^{-1})	32
FOA OS (€ h^{-1})	29
FOA AO (€ h^{-1})	29
MWB LM (€ h^{-1})	15
MWB SM (€ h^{-1})	45
MWB AO (€ h^{-1})	30
MWB PM (€ h^{-1})	15
HC (€ h^{-1})	29
Related cost factors	
Commission (applies to TB and FOA OS) (€ m^{-3})	0.5
Mileage allowances (applies to FA, FOA OS, MWB LM, LC, CC) (€ km^{-1})	0.3
Average distance office to logging site (km)	20

In the analysis of the newly modelled business processes it is assumed that the contractor is able to turn the entire time saved by an improved business process into productive machine work hours (PMH). The potential increase in PMH per year is calculated by the formula:

$$i_a = \frac{u}{(v/p)} i_{op} \tag{1}$$

Where i_a is the potential annual increase in machine utilization (PMH); u is the annual machine utilization (PMH); v is the average volume per operation (m^3); p is the machine productivity (m^3/PMH); and i_{op} is the potential OMWL saving per operation (PMH).

In the As-is model, a utilization of 1500 PMH was assumed. The hourly opportunity costs are:

$$c = \frac{(t_{1500+i_a} - m_{1500+i_a}) - (t_{1500} - m_{1500})}{i_a} \tag{2}$$

Where c is the opportunity costs per hour lost to OWML (€/PMH); t_x is the annual turnover at x PMH per year (€); m_x is the annual machine costs at x PMH per year (€); and i_a is the potential annual increase in machine utilization (PMH).

Published calculators were used for calculating the operating costs per solid m^3 of the chipper (Verkerk et al 2010) and harvester (Väätäinen 2008, 2010). The calculators were adjusted by productivity data from the investigated procurement chain and a test report on a John Deere 1070 D harvester (Weise et al 2009). Staff costs were not taken into account because all contractors work self-employed. Where the supply chain uses the business processes Biomass and Biomass FA, a lower average volume of 90 m^3 per operation was assumed, because in precommercial thinnings the removal per ha is lower than in commercial thinnings or final fellings.

2.2 Improvement of the raw material allocation process

2.2.1 Description of case and the As-is process

The raw material allocation process was defined in expert interviews with chipping contractors in the Finnish region of North Karelia in Eastern Finland. According to the interviews, the As-is process for scheduling of storages, meaning the chronological order in which the storages are to be processed and transported, is determined by the following criteria:

- Logging residues stay spread on the cutovers for one month during the drying season (May to beginning of August, depending on weather conditions) where they dry best before they are forwarded to the roadside storages. After that, they are considered ready for chipping.
- Spatial clusters are established on maps. That means a number of piles which are in close proximity to each other, for example along the same road, are processed at one time to reduce relocation times and costs.
- First in first out: the harvesting residues that were logged first are processed first.

2.2.2 Development of the To-be process "precision supply"

The precision supply approach aims to increasing the energy output of the supply chain, in particular during the peak period from December to February through better use of storage data. Three criteria were defined: average volume, average transportation distance and average moisture content. These criteria replace the decision criteria of the As-is raw material allocation process and used in the simulation scenarios.

2.2.3 Discrete-event simulation modelling

Model structure

The Witness® discrete-event simulation software was used for the case study. The investigated case is a forest entrepreneur based in the city of Ilomantsi in the Finnish region of North Karelia who supplies forest chips from roadside storages of logging residues to a large-scale CHP plant in the city of Joensuu. The supply chain model consists of a large-scale truck-mounted chipper and two chip trucks and involves detailed machine interactions and simulates the operations over a period of one year. The year is subdivided into supply periods according to the variation of demand of the CHP in different seasons (Figure 4):

- Peak period (Peak): high energy demand from December to February.
- Interim period 1 (Interim1): medium energy demand from March to May.
- Summer (Summer): low energy demand from June to August.
- Interim period 2 (Interim2): medium energy demand from September to November.

The model was validated by running it step by step and checking whether the elements of the model behave logically. Finally, the results of the BAU scenario were compared to earlier studies regarding the supply costs (e.g. Laitila 2012) and found to be realistic.

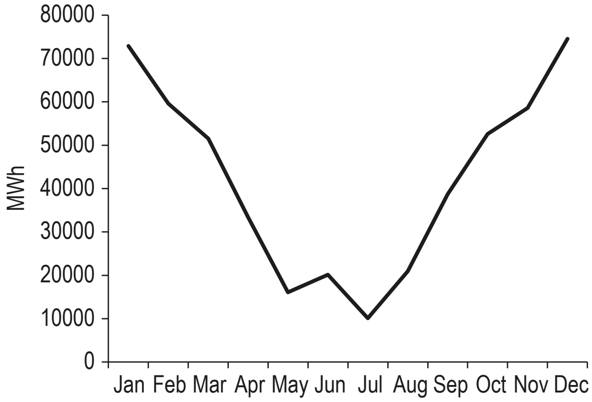


Figure 4. Variation of energy production from forest fuel and the demand for fuel, respectively, of the focal power plant over the year in terms of MWh per month.

Storage data and input variables for machinery

The storage data set was obtained from a large Finnish forest enterprise operating in the region of North Karelia. It included the data on their timber logging operations from the year 2008 to 2010. The data set was analyzed with ArcGIS and the storages with geospatial information matching the entrepreneur's operational area were extracted. From the volume of the timber storages the theoretical occurrence of logging residues from spruce (Picea abies) final fellings was calculated with a conversion factor of 0.44 (Laitila et al 2008). The extractable volume was then calculated by converting the available amount by a factor of 0.7 (Laitila et al 2008). The transportation distance to the plant and the distance to the contractor's business premises were determined by ArcGIS for every roadside storage. Drying curves (Sikanen et al 2013) were used to estimate the moisture contents of storage for every month of the year. A final data pool of 328 storages with a total volume of 57 116 m^3 was used in the simulation. A dry matter density of 445 kg/solid m^3 was assumed (Hakkila 1978). The net calorific value of the biomass was calculated by the formula presented by Alakangas (2005).

The activity times used in the model are based on fixed values (Table 7), distributions (Table 8) and functions. The traveling speed of chipper and trucks was calculated by the functions by Nurminen and Heinonen (2007). The traveling distance between roadside storages was calculated from the spatial coordinates and a road winding factor of 1.6 (Väätäinen et al 2008). Besides the maximum loading volume, the mass of the biomass limits the loading capacity of the trucks. The model calculates the mass per solid m^3 by the following function:

$$m_w = \frac{m_d}{(1 - mc / 100)} \tag{3}$$

Where m_w is the density of wood on a wet basis in kg/solid m^3; *md* is the dry matter density of wood in kg/solid m^3; and *mc* is the moisture content of wood in % when it is being chipped.

The loading is stopped when the max payload is reached.

Table 7. Fixed values used in the simulation models (E_0h = effective working hour).

Value name	Value	Unit	Source
Chipper productivity	60	solid m^3/E_0h	Kärhä et al 2011a, Kärhä et al 2011b, Eliasson et al 2012, Laitila et al 2013
Chipper set up time	0.25	h	Expert interviews
Truck max payload	48	solid m^3	Expert interviews
Truck max payload	33	t	Expert interviews
Indirect loading time	0.2	h	Asikainen 2010

Table 8. Random distributions used in the simulation model.

Value name	Distribution type	Parameter 1	Parameter 2	Source
Occurrence of chipper break downs	negative exponential	mean interval = 9.5 h		Asikainen 1995
Chipper break down duration	negative exponential	mean duration = 0.5 h		Asikainen 1995
Occurrence of inaccessible storage	normal	mean interval = 90 h	Standard deviation= 10 h	Expert opinion
Detour for chipper in case of inaccessible storage	weibull	shape parameter = 1	Scale = 9.833	Distribution fitting
Unloading time for trucks at the plant	normal	mean duration = 0.5 h	Standard deviation = 0.1 h	Väätäinen et al 2005

Simulation scenarios

A total of 7 simulation scenarios were defined (Table 9). In the BAU scenario the raw material allocation was based on the criteria defined in 2.2.1. The volume of the spatial clusters ranged from 900 up to 3600 m^3.

Five simulation scenarios were defined for the precision supply raw material allocation process. The spatial clusters were broken down into smaller units with a more homogenous distribution of moisture contents of the storages of a cluster. The volumes per cluster then ranged from about 500 up to 1800 m^3. According to the criteria defined in 2.2.2, by weighted indices the storages were then assigned to the different supply periods defined in 2.2.4. The practice of drying the material for one month on the cutovers during drying seasons was in place.

Table 9. Overview of the simulation scenarios. The abbreviation describes the factors taken into account: Td = transportation distance, Mc = moisture content, Vol = storage volume. The weighting factor describes the impact of each factor on the ranking in the different scenarios: the higher the factor, the higher the importance of the factor.

Scenarios	Description	Spatial clusters in use	Abbreviation	Weighting factor		
				Td	Vol	Mc
1.	Business as usual	yes	BAU	-	-	-
2.	Precision supply 1	yes	TdMcVol	0.33	0.33	0.33
3.	Precision supply 2	yes	Td	1	0	0
4.	Precision supply 3	yes	Vol	0	1	0
5.	Precision supply 4	yes	Mc	0	0	1
6.	Precision supply 5	yes	TdMc	0.5	0.5	0
7.	Random supply	no	RAND	-	-	-

2.2.4 Economic analysis

The simulation model provided data on the productivity of the supply chain and recorded work time elements for chipper and trucks. For calculating the costs of forest biomass supply chains, an Excel-based cost calculator was developed. For calculation of the costs of chipping, the key figures were effective machine work hours (E_0h), driving time, other work time and annual production in terms of solid m3 and MWh (1MWh = 3.6 MJ). The key figures for the cost calculation for the chip truck were average transport distance per load, average time consumption per load, average number of loads per day and average amount of MWh and solid m^3 per load. The cost calculator for the mobile chipper was obtained from Jylhä (2013) and some cost parameters supplemented by values given by the Finnish Machine Contractor Association. The calculator and cost parameters for the chip trucks were obtained from the Finnish transports and Logistics association (SKAL). The values of the cost parameters corresponded to the average price levels of the year 2013. Investment prices without value added tax for the mobile chipper and chip trucks were 770 000 € and 264 000 € per piece. The depreciation period was 7 years for both and the interest rate was 5%.

2.3 Improvement of data management and information logistics through ICT

2.3.1 Description of the case

A SCM tool designed for forest biomass supply was investigated. The server-based application worked as a link between the functional units of the supply chain. The central data management system kept them updated on the status of work orders and storages, and thus simplified the tactical and operational planning as well as the storage management. The data exchange and communication happened by means of the Internet, SMS, email, mobile phones and paper printouts, if required. The SCM application allowed the integration of interfaces to third-party systems such as truck scales and enterprise resource planning software.

By means of a cost-benefit analysis (CBA) the economic effects of utilizing the SCM application was investigated in case studies of two different Forest Owners Associations (FOAs) in Finland. FOA1 supplied 150 000 loose m^3 of biomass per year; FOA2 37 000 loose m^3. Both FOAs were experienced users of the application. The costs for the application were defined by real expenses from their bookkeeping. The benefits were identified through expert estimations of staff who had been working with the FOA for several years before and after the implementation of the SCM application.

2.3.2 Research material

The CBA covered a period of 10 years. Over such a timespan, cost and benefit factors underlie changes due to the change of prices levels. For this reason, corresponding factors based on statistical data were applied in the calculation adjusting the costs and benefits every year. The annual change (%) of staff costs was based on the development of labor costs in the Eurozone (Eurostat 2010). Data on the development on license fees and consultation days were not available, so the same percentage was used to adjust their price levels. The annual decrease of the price of portable computers was based on statistics on their price development from 2005 to 2010 by Statistics Finland (2010b). It was assumed that the decrease would not remain on such a high level for the coming 10 years. The annual adjustment of additional profits through decreased moisture contents and of other costs is based on the inflation rate in the Eurozone (Eurostat 2010). The annual change percentage of 0% used for mobile phones practically means a decrease in price of 2% per year which is verified by statistics on communication costs (Eurostat 2009). The change of transportation distance savings was based on the price trend for diesel oil in Finland (Statistics Finland 2010a). However, due to the progressive scarcity of oil, the annual change was set to a higher level than suggested by the price trend over the past 10 years.

Table 10 lists the different cost and benefit factors which apply for FOA1. FOA1 was involved in the development of the SCM application and got some reductions, as a result of this. They were remitted the purchasing price of the application as well as costs for the five consultation days of the starting training, which usually amount to 1500 € per day. The increase of phone costs originated from the SMS system which was used for exchanging data between field staff and the SCM application. Each data-SMS cost 0.6 €. Even though, the SCM application decreased the general need for communication via mobile phones, additional expenses of 20 € per month apply. Table 11 lists the cost and benefit factors of FOA2. As they are a normal user, they did not get any price reductions.

The expert stated that a familiarization phase of one year was required to use the full potential of the application. For this reason correction factors were used in the calculation to simulate a learning curve: In the first year the benefits are assumed to be 0. In year two 50% and in year three 70% of the annual benefits were reached. From year four onward full benefits are reached.

Table 10. Cost and benefit factors of FOA1. The table describes the name of the factor, which values it is composed of, at which points in time it occurs, its basic amount and the annual change it is subject to.

Factor	Composition of factor	Occurrence	Basic amount	Annual change
Costs				
Purchasing			0 €	
License fees	960 €/license/year 5 licenses	annually	4 800 €	3%
Phone costs	240 €/person/year 5 persons	annually	1 200 €	0%
Starting training	0 €/consultation day 5 days 1 trainee 300 €/day/trainee	implementation	1 500 €	
Update training	1 500 €/consultation day 1 day 5 trainees 300 €/day/trainee	annually	3 000 €	3%
Portable computers	4 pieces 4 years lifetime 1 500 €/piece	every 4th year	6 000 €	-10%
Other costs		annually	1 000 €	2%
Benefits				
Work time savings	0.5 man years 65 000 €/man year	annually	32 500 €	3%
Transportation savings	15% savings 11 500 km saved 0.6 €/km	annually	6 750 €	7%

Table 11. Cost and benefit factors for FOA2: The table describes the name of the factor, which values it is composed of, at which points in time it occurs, its basic amount and the annual change it is subject to.

Factor	Composition of factor	Occurrence	Basic amount	Annual change
Costs				
Purchasing		implementation	2 000 €	
License fees	960 €/license/year 5 licenses	annually	4 800 €	3%
Starting training	1 500 €/ consultation day 3 days 5 trainees 300 €/day/trainee	implementation	9 000 €	
Update training	1 500 €/consultation day 2 days 5 trainees 300 €/day/trainee	annually	6 000 €	3%
Portable computers	5 pieces 4 years lifetime 1 500 €/piece	every 4th year	7 500 €	-10%
Other costs		annually	1 000 €	2%
Benefits				
Working time savings	2 man years 65 000 €/man year	annually	130 000 €	3%
Transportation savings	10% savings 4 000 km saved 0.6 €/km	annually	2 400 €	7%
Moisture content decrease	5% 0.24 €/loos m^3/year	annually	8 880 €	2%

2.3.3 Economic analysis

The profitability of the SCM application was calculated using the method of net present value (NPV) with the following formula (Levy and Sarnat 1994):

$$NPV = \sum_{t=1}^{n} \frac{S_t}{(1+k)^t} - I_0 \tag{4}$$

where S_t is the expected net cash receipt at the end of year t; I_0 is the initial investment outlay; k is the discount rate; n the duration of the project in years. In the calculation a range of interest rates of 4%, 6%, 10% and 15% was chosen in order to cover different options for reinvesting profits.

3 RESULTS

3.1 Reengineering of the biomass procurement process

3.1.1 Business process modelling

To-be process

The actions proposed in the process modelling (Figure 5) led to major changes (Figure 6). 41 activities could be eliminated, leaving 142.

FUs	As-is	Proposed action	To-be
FOA OS FA LC CC	Most FUs visit work site once or even more often for data collection	● Standardised data collection through stand info form and price matrix ● Digital data exchange	One FU collects data for all FUs
FOA OS LC	FOA OS and LC visit work site together to negotiate price for logging	● Stand info form ● Logging price matrix	FOA OS collects data needed by LC and determines logging price through price matrix
FOA OS LC	FOA OS monitors logging on a daily basis	● Reward system based on quality of work ● Empowerment of contractors	FOA OS checks work site after logging is finished
TB FOA OS	TB measures piles after logging is finised	● Shift task to FOA OS ● Eliminate TB from process	FOA OS measures piles during final checking of work site
MWB LM FOA OS	MWB LM visits fuel piles and deremines quality and price	Fuel price matrix	FOA OS determines fuel quality and price according to price matrix when measuring the piles
MWB LM CC TC	MWB LM monitors chipping operation	● Standardised digital data exchange ● Empowerment of contractors	CC and TC execute operation without being monitored
MWB SM MWB AO	MWB SM matches invoices with delivery notes	● Shift task to MWB AO ● Eliminate MWB SM from process	MWB AO matches invoices with delivery notes while doing the accounting

Figure 5. Alterations made during business process modelling from the As-is to the To-be process. (Acronyms are defined in Table 3).

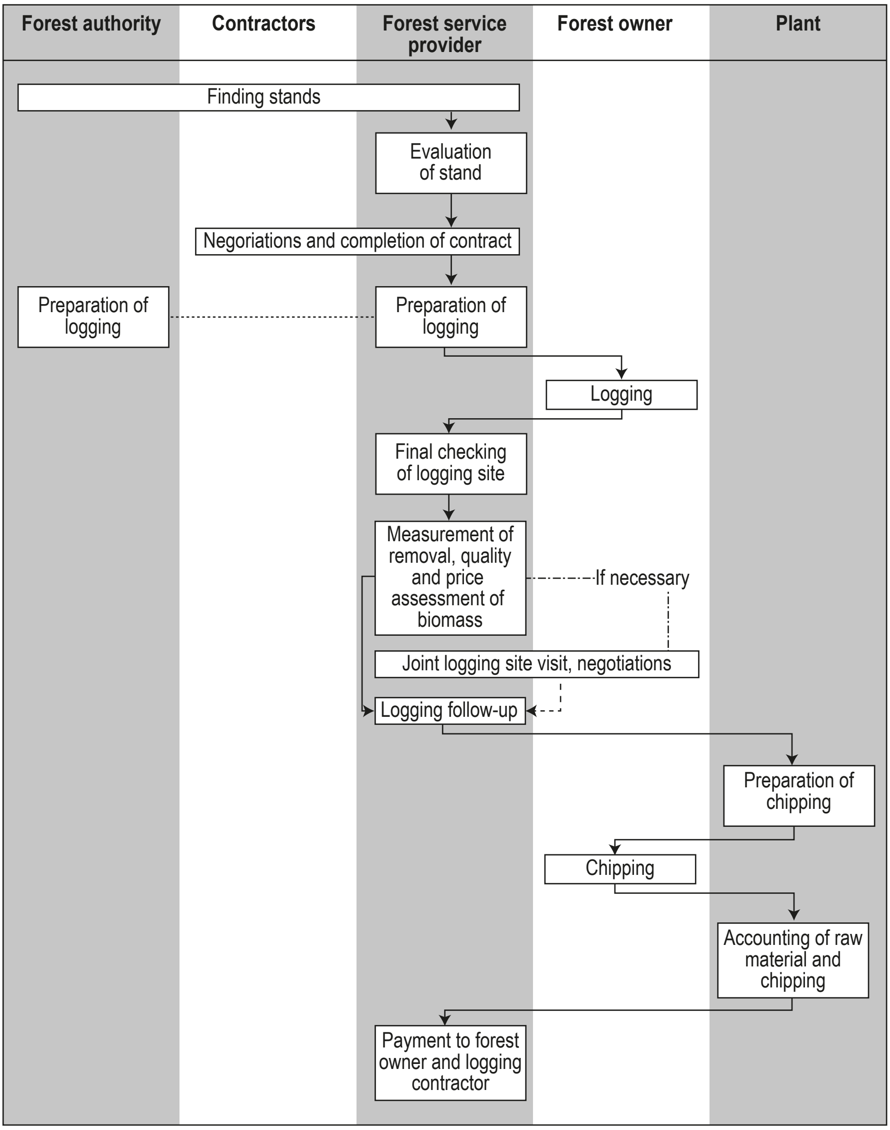


Figure 6. Sub-processes of the To-be process (Functional units grouped as shown in Table 3).

Biomass process

The model of the Biomass business process involved the measure proposed in the To-be process and further actions (Figure 7), aiming to minimize the OMWL. The new process setup (Figure 8) was further streamlined, resulting in the elimination of another 53 activities. The difference relative to the As-is process was then 94.

FUs	To-be	Proposed action	Biomass
FO FA FOA OS	FA and/or FOA OS visit the stand together with the FO for price negotiations	● Price matrix	MWB OS negotiates with the FO on the phone on basis of a price matrix
FA FOA OS	FA or FOA OS prepare logging site by marking trees to be removed and skid trails	● Empowerment of LC ● Shift task to LC	FOA OS only marks stand borders if necessary. LC makes the decision about removal and lay out of skid trails while executing the operation
FOA OS LC	FOA OS monitors logging on a daily basis	● Empowerment of LS ● Task elimination	FOA OS checks work site after logging is finished

Figure 7. Alterations made to the To-be business process. (Acronyms are defined in Table 3).

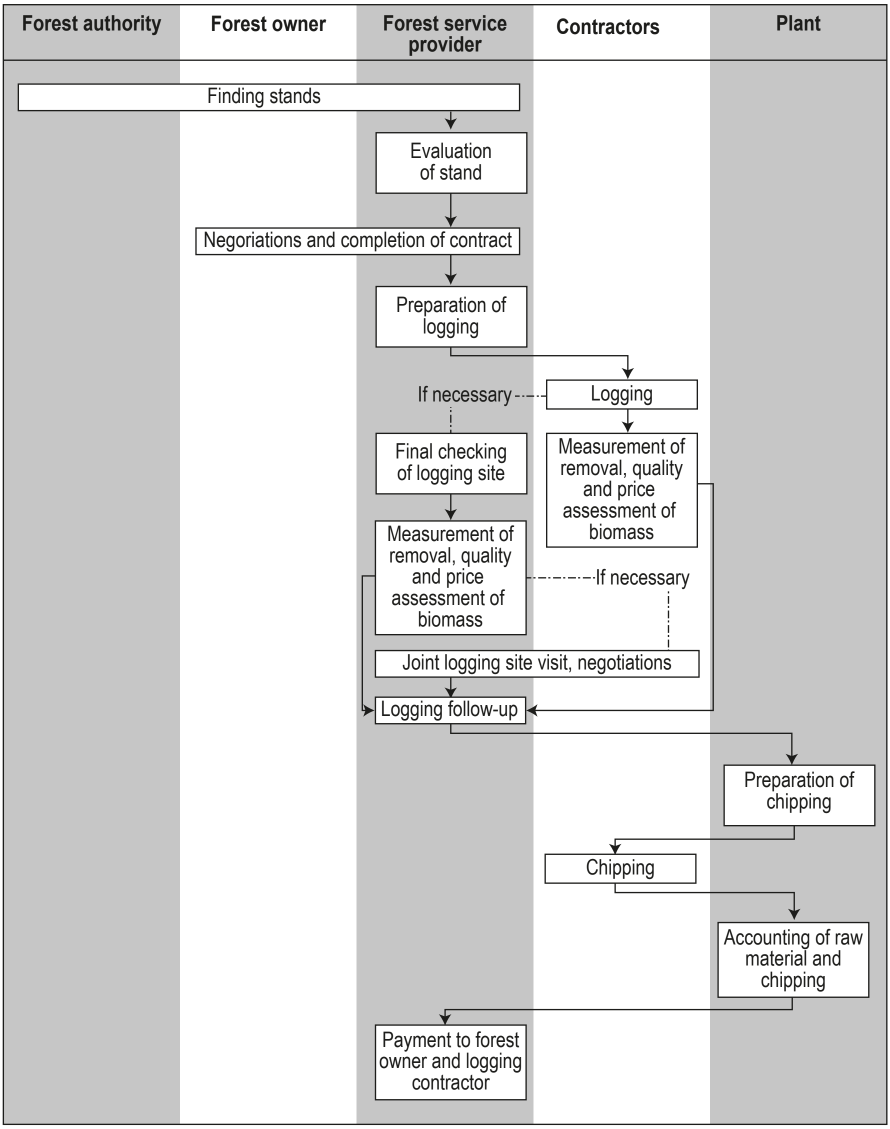
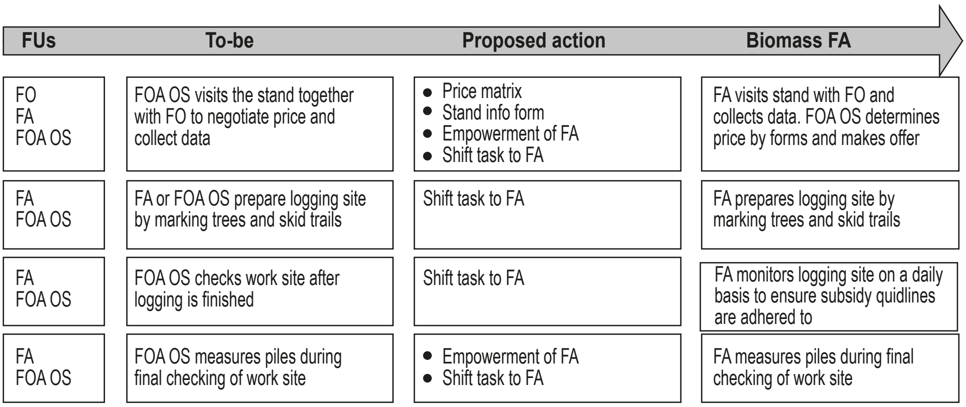


Figure 8. Sub-processes of the Biomass business process. (Functional units are grouped as shown in Table 3.

Biomass FA process

Given that certain guidelines are followed, forest owners in the state of Bavaria are eligible for a subsidy of 400 €/ha for precommercial thinnings. Monitoring that these guidelines are followed, the Forest Authority is highly involved in the procurement process. For this reason, in the Biomass FA process further actions were undertaken (Figure 9) which put the Forest Authority in charge of large parts of the business process (Figure 10) to lower the OMWL of the entrepreneurial side of the supply chain. These action reduced the number of activities by another 80 relative to the As-is process, meaning a final number of 103.



FUs	To-be	Proposed action	Biomass FA
FO FA FOA OS	FOA OS visits the stand together with FO to negotiate price and collect data	● Price matrix ● Stand info form ● Empowerment of FA ● Shift task to FA	FA visits stand with FO and collects data. FOA OS determines price by forms and makes offer
FA FOA OS	FA or FOA OS prepare logging site by marking trees and skid trails	Shift task to FA	FA prepares logging site by marking trees and skid trails
FA FOA OS	FOA OS checks work site after logging is finished	Shift task to FA	FA monitors logging site on a daily basis to ensure subsidy quidlines are adhered to
FA FOA OS	FOA OS measures piles during final checking of work site	● Empowerment of FA ● Shift task to FA	FA measures piles during final checking of work site

Figure 9. Alterations made during the modelling of the Biomass FA business process. (Acronyms are defined in Table 3)

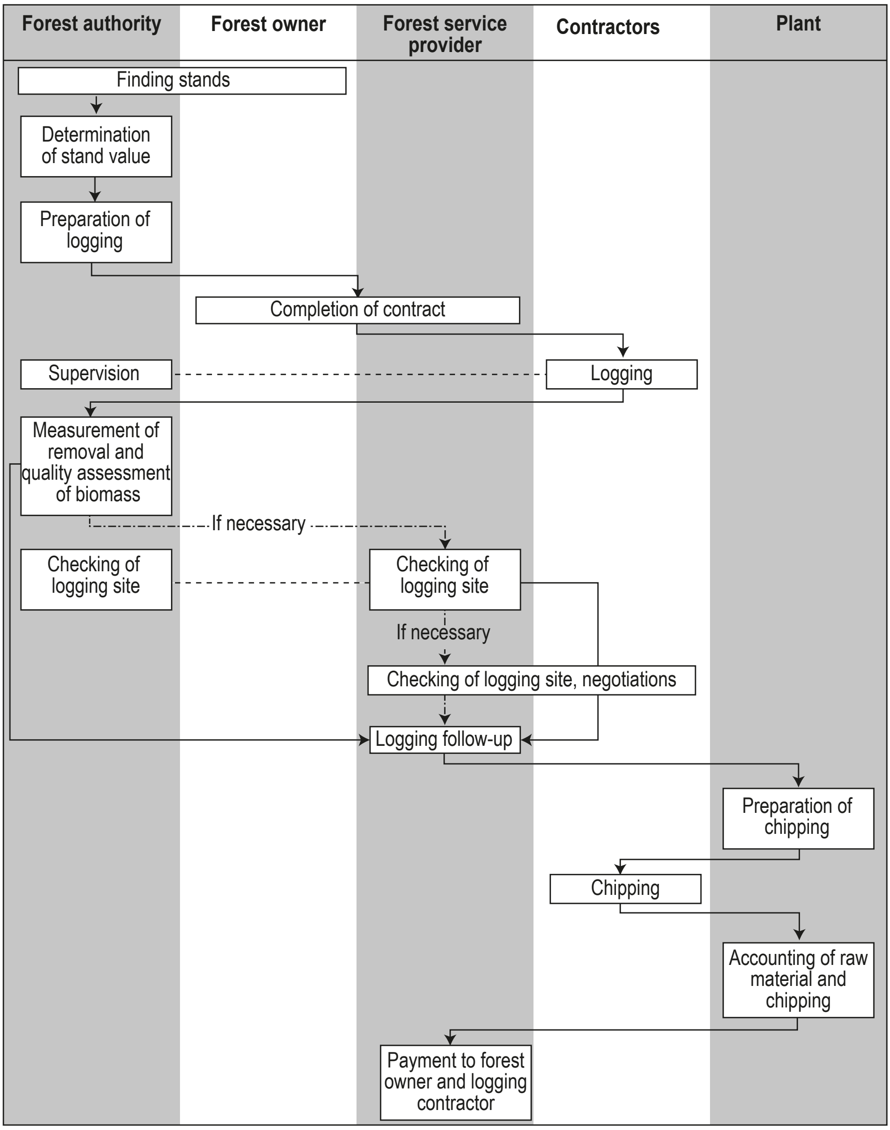


Figure 10. Sub-processes of the Biomass FA business process. (Functional units are grouped as shown in Table 3).

3.1.2 Economic analysis

The calculations resulted in opportunity costs of 81 €/h for the logging and 121 €/h for the chipping contractor. Table 12 shows the costs related to the OMWL in the As-is process. Depending on the probability of errors, all newly designed business process provided considerable saving potentials (Table 13, Table 14, Table 15). Only the Biomass FA process may add costs if the probability of errors is at 100%.

Table 12. Organizational and managerial work load and related costs of the As-is business process. (Acronyms are defined in Table 3).

OMWL (min m^{-3})	Commission (€ m^{-3})	Staff costs (€ m^{-3})	Mileage (€ m^{-3})	Total (€ m^{-3})
13.80	1.00	8.19	0.75	9.94

Table 13. Organizational and managerial work load and related costs of the To-be business process. The name of the scenarios describes the probability of failures. In the scenario "100%" in all transactions failures occur. In the scenario "0%" no failures occur. (Acronyms are defined in Table 3).

Scenario	OMWL (min m^{-3})	Commission (€ m^{-3})	Staff costs (€ m^{-3})	Mileage (€ m^{-3})	Total (€ m^{-3})	Difference to As-is (%)
100%	10.48	0.50	7.15	0.34	7.99	-20%
75%	9.65	0.50	6.30	0.34	7.14	-28%
50%	9.38	0.50	6.17	0.34	7.01	-29%
25%	8.74	0.50	5.62	0.34	6.45	-35%
0%	8.30	0.50	5.22	0.34	6.06	-39%

Table 14. Organizational and managerial work load and related costs of the Biomass business process. In the scenario "100%" in all transactions failures occur. In the scenario "0%" no failures occur. (Acronyms are defined in Table 3).

Scenario	OMWL (min m^{-3})	Commission (€ m^{-3})	Staff cost (€ m^{-3})	Mileage (€ m^{-3})	Total (€ m^{-3})	Difference to As-is (%)
100%	11.46	0.5	7.99	0.27	8.76	-12%
75%	9.79	0.5	6.61	0.27	7.37	-26%
50%	8.38	0.5	5.44	0.20	6.14	-38%
25%	7.35	0.5	4.62	0.20	5.32	-47%
0%	6.50	0.5	3.99	0.13	4.62	-53%

Table 15. Organizational and managerial work load and related costs of the Biomass FA business process. In the scenario "100%" in all transactions failures occur. In the scenario "0%" no failures occur. (Acronyms are defined in Table 3).

Scenario	OMWL (min m^{-3})	Commission (€ m^{-3})	Staff cost (€ m^{-3})	Mileage (€ m^{-3})	Total (€ m^{-3})	Difference to As-is (%)
100%	16.04	0.5	9.94	0.80	11.24	13%
75%	14.30	0.5	8.78	0.67	9.39	-6%
50%	12.98	0.5	7.86	0.60	8.45	-15%
25%	12.09	0.5	7.10	0.53	7.68	-23%
0%	10.78	0.5	6.22	0.40	6.79	-32%

3.2 Improvement of the raw material allocation process

The analysis and comparison showed that the scenarios of the raw material allocation process Precision Supply outperform the BAU approach (Figure 11). The scenarios using transport distance, moisture content and volume (TdMcVol) , transportation distance alone (Td) and transport distance with moisture content (TdMc) as storage selection criteria provided the largest increase in total energy output per year (7%, 8% and 7%). Their benefit becomes particularly evident during the Peak period, when the energy demand is highest (increase of 23%, 27% and 29%) (Table 16). Not least, the lower moisture content (Figure 12) of the material led to these results. A decrease in moisture content leads to improved calorific value of the material. Furthermore, it improves the mass to volume ratio, so that the loading volume of the trucks was utilized better. Therefore, a decrease of the average moisture content of 4.38% in the Peak period of the Mc scenario increased the average energy density per truck load by 12.16% relative to BAU, the decrease of 3.5% in the TdMc scenario to an 8.88% higher energy content per truck load (Table 16).

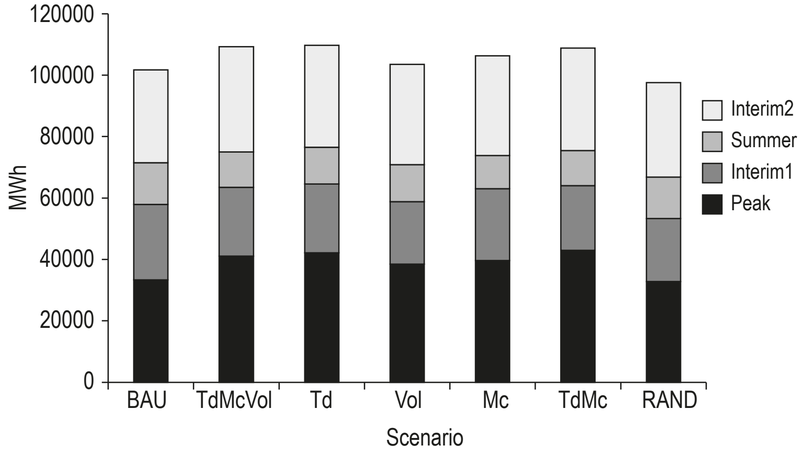


Figure 11. Deliveries to the plant per year and supply period for different scenarios. (Abbreviations used as described in Table 9).

Table 16. Overview of the productivity figures in Peak period. (Abbreviations used as described in Table 9).

Scenario	MWh/ MWH chipper	MWh/ MWH truck	MWh/ km trucks	m³/ load	MWh/ load	MWh	No of loads	Moisture content (%)
BAU	40.89	18.93	0.55	36.15	74.28	33308.35	448.43	50.39
TdMcVol	49.79	23.18	0.85	37.95	78.90	41094.72	520.86	48.21
Td	51.09	23.70	0.94	37.31	77.36	42172.81	545.14	48.78
Vol	46.50	21.72	0.71	37.34	77.44	38507.86	497.29	48.65
Mc	47.70	22.31	0.73	39.60	83.31	39593.48	475.29	46.01
TdMc	51.72	24.09	0.94	38.63	80.87	42942.52	531.0	46.89
RAND	38.82	18.25	0.58	36.79	75.95	32766.38	431.43	49.57

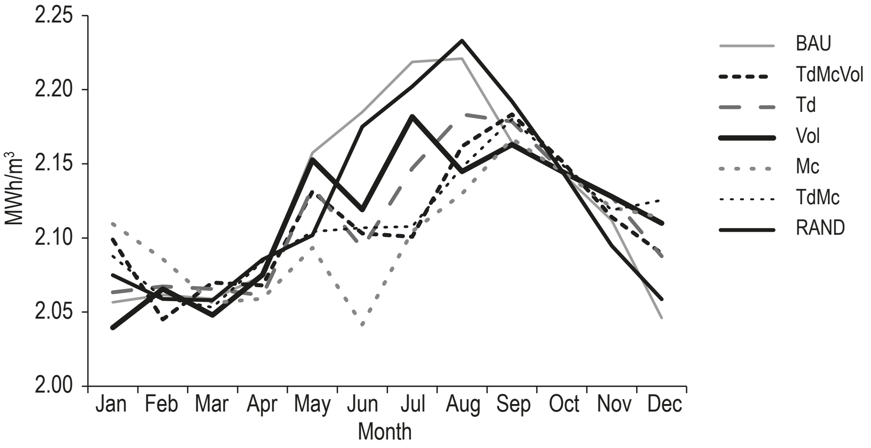


Figure 12. Monthly average energy density of the biomass delivered to the plant in different scenarios.(Abbreviations used as described in Table 9).

Table 17. Overview of supply costs and other key figures per year. (Abbreviations used as described in Table 9).

Scenario	Chipping costs (€/MWh)	Transport costs (€/MWh)	Total costs (€/MWh)	MWh/ km	Average moisture content (%)	Average MWh/load	Annual supply to the plant (MWh)
BAU	3.41	3.59	7.00	0.63	45.24	82.64	101716
TdMcVol	3.29	3.30	6.60	0.73	45.51	83.63	109288
Td	3.25	3.29	6.54	0.72	45.66	82.86	109702
Vol	3.39	3.53	6.92	0.65	45.50	83.02	103520
Mc	3.34	3.43	6.77	0.67	45.61	83.74	106279
TdMc	3.28	3.32	6.60	0.71	45.22	83.98	108845
RAND	3.65	3.76	7.41	0.62	44.69	83.81	97528

The cost comparison demonstrates that all precision supply scenarios decrease the supply costs of the year relative to BAU (Table 17). The lowest benefit occurred in the Vol scenario where the costs could be decrease by only 1%. TcMc and Td scenario, however, cut the supply costs by 6% and 7%, respectively.

3.3 Improvement of data management and information logistics through ICT

3.3.1 Cost-benefit-analysis of Forest Owners Association 1

The CBA of using an SCM application demonstrated their benefits over the considered period (Figure 13, Figure 14). Due to the simulated learning curve there were no benefits in year 1 and 2 and only modest ones in year 3. After ten years the net benefit reached a maximum

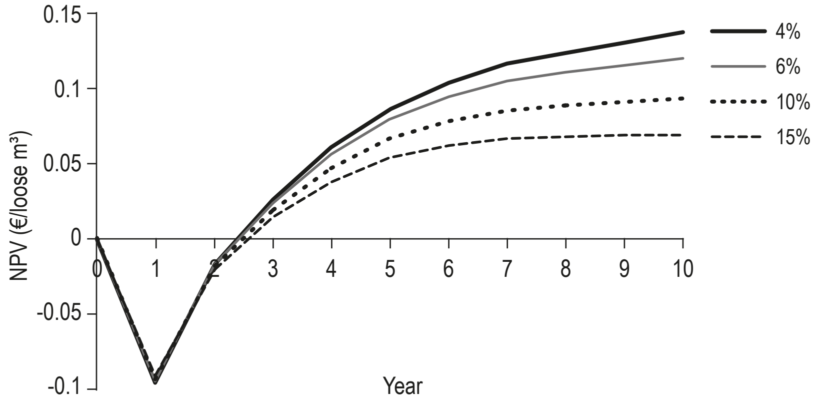


Figure 13. Net present value in €/loose m³ for FOA1 considering different rates of return and a period of 10 years.

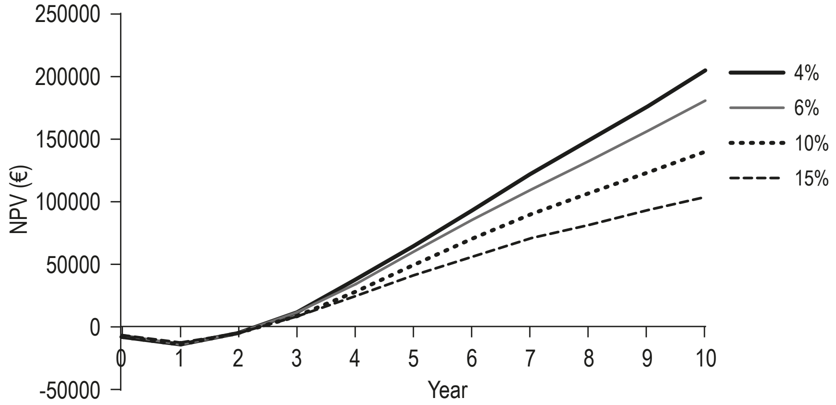


Figure 14. Net present value for FOA1 considering different rates of return over a period of 10 years.

value of 204 674 € at an interest rate of 4% and a value of 0.136 € per procured loose m^3. At an assumed higher return rate on investment of 15%, the NPV decreased to 103 234 € (0.069 €/loose m^3).

3.3.2 Cost-benefit analysis of Forest Owners Association 2

The values of the CBA of FOA2 were considerable higher relative to FOA1 (Figure 15, Figure 16). Due to the high estimations of savings, the NPV turned positive after year 1, despite the simulated learning curve. The range of benefits regarding different rates of return varied between 931 524 € (2.517 €/loose m^3) at 4% and 496 524 € (1.342 €/loose m^3) at 15%.

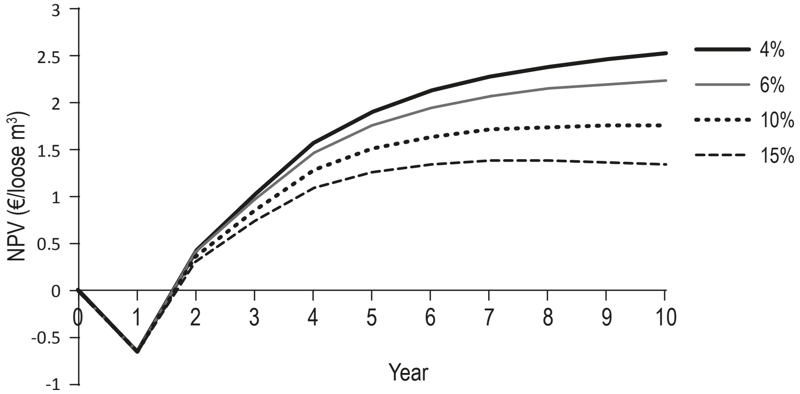


Figure 15. Net present value in €/loose m³ for FOA2 considering different rates of return and a period of 10 years.

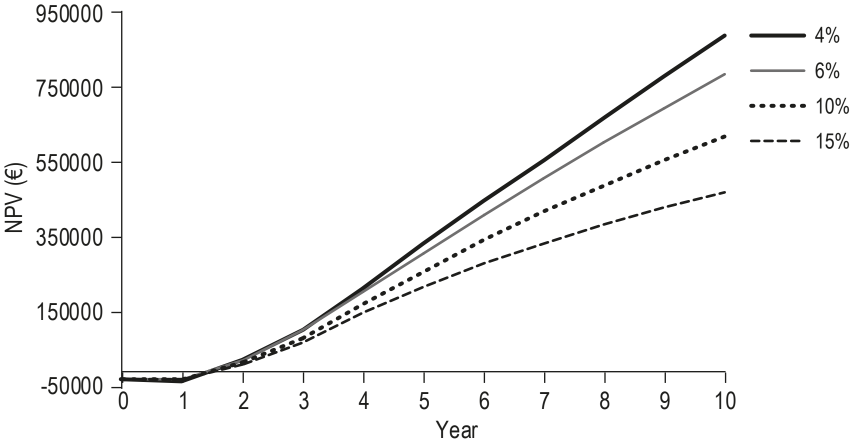


Figure 16. Net present value for FOA2 considering different rates of return and a period of 10 years.

4 DISCUSSION

Improving the costs efficiency of forest biomass to energy supply chains has been on the research agenda for many years. The economics of operations is critical due to high procurement costs and low product value of residual forest biomass. Developing and testing of new, more productive machinery has been the center of attention usually. Recent developments indicate that machine productivity is saturating and no rapid improvement of performance is to be expected. What has become a problem is the productivity of the supply system. A supply system here means all operations including also supporting processes such as organization and management, storage management, raw material allocation and information logistics. Essentially, what is required from a holistic perspective on the topic of forest technology is establishing supply systems which enable the actors to increase the overall cost efficiency of these systems. That means being able to make use of the high machine productivity and to decrease the costs for staff involved in the organization and management of operations.

The present thesis demonstrated the potential of process improvement measures to achieve both aims. The business process mapping and reengineering of paper I and II gave an insight into what has largely been a black box before: the organization and management of small and medium scale forest biomass supply chains. It revealed the costs related to it for all actors. Furthermore, the study demonstrated how, through comparatively easy and low-cost measures, the business process can be streamlined and costs cut. In particular, for the machine contractors the approach provided considerable saving potentials through releasing them from organizational and managerial tasks and giving them more time for operating their machines which is the actual value adding activity from their perspective.

Article III improved the raw material allocation process through better use of data on roadside storages. The new process improved the efficiency of operations on various levels for both contractors and the plant, in particular during peak periods. The contractors benefit from higher efficiency of their machinery and better utilization of the transport capacity. Essentially, this means higher profits. The plant benefits from getting more wood-based energy delivered by the supply chain which means less need for buffer storages which add capital costs to operations. Furthermore, dryer material means more energy can be generated from the same volume and transportation is more energy efficient leading to less emissions per supplied energy unit. Essentially, the improved raw material allocation process means less costs and more energy delivered throughout the year. Finally, increasing the energy content of the biomass means a better utilization of a limited resource. For these reasons, the improved raw material allocation process creates a win-win-win situation for the contractors, the plant and the environment.

In article IV, the cost and benefit of investing into information and communication technology for improved information logistics were investigated. Even though such applications were introduced to forestry years ago, forest biomass business actors seem to spare the investment because they are not convinced of the benefits. The study proved that medium and long-term investments into ICT are not only safe but provide a considerable cost-saving potential through simplifying the management of operations and accelerating and standardizing data exchange.

Thorsén et al (2011) in their summary report of Skogforsk's R&D program Efficient Forest Fuel Supply Systems say that the means for increasing the use of forest biomass are "increased efficiency, lower costs and higher fuel quality". The present thesis has addressed all three of these means by applying measures of process improvement and demonstrated the remarkable benefits lying with this method. Increasing the productivity and cost-efficiency of machinery requires considerable sums of money for research and development and, consequently, new machinery is expensive for the contractors to buy and to operate. The present thesis showed ways of how to improve the efficiency of existing procurement/supply system which can be achieved at much lower costs but considerably increase the system productivity and efficiency, nonetheless.

The present thesis has applied process improvement in three different case studies. The method of BPR was applied according to earlier guidelines, in particular regarding BPR in context of small and medium-scaled enterprises (McAdam 2002). Notice has to be given that applying reengineering of business processes without implementation of ICT is a somewhat artificial approach as it neglects the additional benefit which could be gained from combining both (Grover and Malhotra 1997). However, this approach was chosen deliberately. Article I and II investigated how reconsidering and streamlining existing practices can improve the cost-efficiency of operations without making investments into technology.

It was chosen to view the business processes as complex dynamic systems. The sociopolitical dimension of the business process is largely neglected by this perspective (Melão and Pidd 2000). However, in article I and II the aim was to investigate in detail which actors, tasks and activities are involved in the business process, which costs lie with it and what the saving potentials of BPR are. The approach of viewing the business processes as complex dynamic systems served this purpose well as it allowed applying discrete-event simulation. Röser (2012) discussed the sociopolitical dimension of the business processes in detail. He found the lack of trust among actors and resistance to change to be the largest obstacle in the way towards streamlining and integrating business processes. Implementing the business processes developed in article II undoubtedly would require taking these issues into consideration and addressing them, but was not part of the study.

The wide variety in the range of costs of organizational and managerial tasks becomes evident from the studies of Hug (2004) and Baumann (2008). Despite investigating similar forest undertakings in the same working environment, Baumann's study results in OMWL costs of only 2.26 €/m^3, while Hug identified costs amounting to 7.65 €/m^3. The OMWL costs of comparable FUs (FOA OS, FOA AO, TB) identified in the present study are 3.50 € (As-is). In this context the high hourly staff costs of 47 €/h used by Hug must be mentioned. Having a look at the time consumption per m^3 provides a clearer picture. While Hug determined an OMWL of 9.6 min/m^3, the related FUs in the present study spend 6.1 min/m^3. Hug's and Baumann's studies also identified cost saving potentials. Using a purely mathematical approach, Baumann found a comparatively low saving potential of 0.26 €/m^3 (11.5%). Hug's approach again, involving business process reengineering enabled by Information and Communication Technology, resulted in a considerable cost saving potential of 4.34 €/m^3 (56.7%). The expected cost saving potential of the To-be process of the present study for the FUs mentioned above is 1.15 € (33.1%). The Biomass and Biomass FA process provides potential savings of 1.06 €/m^3 (30%) and 1.88 €/m^3 (53.7%), respectively.

Through technological development and learning-by-doing, the supply costs of wood chips from logging residues in Sweden have decreased by 32% in the period from 1983 to 2003 (Junginger et al 2005). The results for the investigated case show a similar improvement potential by streamlining business processes alone. Admittedly, compared to the Nordic countries forest biomass to energy is a rather immature branch of forestry. Therefore, the improvement potential in terms of organization and management may be greater. However, the methods of process improvement can be applied to all kinds of supply chains. Independent of the machine setup, an increase in cost efficiency and productivity can be achieved. The problem of lacking supply chain thinking found in earlier studies (Bodelschwingh 2006) also became apparent in the present case. Actors in the supply chain acted as stand-alone companies and did not share information they had gathered, which forced other FUs to perform these activities redundantly. By standardizing and improving the data exchange, activities like stand visits for data collection could be done only once, saving other FUs considerable work effort.

In machine cost calculations, organizational and managerial work is covered under overhead costs to which a fixed value is assigned (Laitila et al 2010, Jylhä 2013). According to Junginger et al (2005) overheads were within a range of 10% to 15% over the past 25 years. In the present case, where opportunity costs are taken into account, this is only true for the chipper contractor (16%). The logging contractor's overheads however are considerably higher with a value of 25%. It should be noted that the calculation of the OMWL costs in the present study did not take into account costs for office equipment or communication costs, which are usually part of overhead costs in machine cost calculations.

For increasing the efficiency of machinery, usually considerable investments into research and development are required. For example, the whole tree bundler Fixteri has been being developed over a number of years. The productivity has increased by 38–77% from first to second prototype (Jylhä and Laitila 2007, Nuutinen et al 2011). The third prototype Fixteri X15a again had a 2.1–2.3 times higher efficiency than the previous prototype (Nuutinen and Björheden 2014). Undoubtedly, the achieved increase is remarkable and proves the potential that still lies with machine development, in particular at the early stages of machine development and readiness levels of technology. Further increasing machine productivity is required in particular when considering the high hourly operational costs in a forestry context. However, research and development and new machinery consequently are costly. The present study achieved a considerable increase in the cost-efficiency of operations with measures that require far less financial investments and time. Furthermore, the improvement potential of BPR is not dependent on the machinery involved in the supply chains. However, in the present study, the cost-efficiency was increased through potentially increasing the machine utilization, while the development of Fixteri increased the productivity per effective machine work hour (E_0h). Therefore, the results are not directly comparable.

The increase of the cost-efficiency of operations not only has an effect on the economics of operations, but also on the amount of biomass economically available. Laitila et al (2010b) investigated the availability of energy wood from different small stem energy wood around the Finnish city of Jyväskylä relative to the procurement costs. Their study showed that a decrease of about 20% in procurement costs would raise the available energy wood from whole trees from 10 000 solid m^3 to about 250 000solid m^3 per year. Karjalainen et al (2004) estimated the marginal costs for felling residues for different European countries. In Poland a procurement cost reduction of 24% would almost double the available logging residues, while in Finland the availability would quadruple at a reduction of 19%. The BPR in the present thesis was conducted in a case study in Germany, so whether similar results improvements are possibly in other regions is uncertain. Unfortunately, similar cost supply availability studies for Germany could not be obtained. However, the availability studies indicate what effect improvements of the cost-efficiency of supply systems achieved in the present thesis may have on the availability of energy wood. It is to be assumed that small and medium-scale supply chains need external support from researchers or personnel which is acquainted with the concepts and pitfalls of BPR. After all, people in forestry may be reluctant to embrace BPR, even more so if they are not convinced of the benefits. Paper I and II gave an actual value for the improvement potential of BPR. This might convince and encourage practitioners in the field of forest biomass to energy procurement to rethink their business processes and to embark corresponding projects.

Paper III aimed to improve the raw material allocation process for a forest biomass supply chain. It used discrete-event simulation to investigate the effects of an information-based process on the productivity. When investigating hot chains for forest biomass supply machine interactions are a crucial factor. For this reason, the method of discrete-event simulation achieves a higher level of exactness of the results than static modelling methods (Asikainen 2010) and was therefore used.

The model was developed based on expert interviews. The general logic of machine behavior and interaction was found to be similar to earlier models (Asikainen 1995, 2010). However, a number of additional features were implemented in the present model to make it behave closer to reality.

Besides traveling between roadside storages, the model took the traveling to the roadside storages at the start of the shift and back to the parking positions at end of shift into account. That led to a lower machine utilization compared to earlier studies. Here the chipping made up between 33–38% of the time elements, depending on the simulation scenario. Spinelli and Visser (2009) investigated forest biomass supply operations and found utilization rates of 73.8% on average. In this study, only the operations at the roadside were investigated, meaning relocation times of the machinery were not considered. Holzleitner et al (2013) found a utilization rate of 49% in a case study in Austria. Their study included relocation times only between storages. An additional reason for the comparatively low utilization rate in the present study is that only two trucks worked in the supply chain, independent of transportation distances. According to experts, the utilization rate found in the present study is realistic in the working environment of North Karelia.

The simulation ran over a period of a whole year. Therefore, varying shift lengths were used to simulate the fluctuation of the fuel demand of the plant. The shift length of 4 hours during the Summer period, however, is not applied in practice. According to the expert interviews, during times in which the demand is low and thus the supply chains work at low capacity, for a few days they work normal shifts and have time off on other days when the fuel demand of the plant is covered. No data on the volumes supplied by a single supply chain could be obtained. Consequently, the supply chain in the present model is not demand driven what would be required to model the shifts according to the practice. To compensate for this shortcoming and to take the low production in Summer into account, the present shift system was used.

The drawback of the approach is that it leads to a slight overestimation of relocation times and costs at beginning and end of shifts in the Summer period. The simplification of the shift system was applied in all scenarios. That means the same shift system was in use in the precision supply scenarios as well as in the business-as-usual to which they were compared. Therefore, the simplification should not have a negative impact on the comparability and consequently on the validity of results.

Finally, the model simulated load limitations based on the maximum loading volume of the trucks and weight limitations. High moisture content preventing full utilization of the max loading volume of trucks is a problem practitioners in the field struggle with (Lahti and de Bie 2013). By taking this into account in the model, the improvement potential of the information-based raw material allocation process regarding this problem could be demonstrated. Decreasing the moisture content increases the energy density of the material. In addition, it improves the mass per volume ratio. During Peak period, the Mc scenario decreased the moisture content by 4.38% on average, leading to an increase of the average energy content per truck load of 12.16%. A decrease of 3.5% in the TdMc scenario led to an increase of delivered energy content per truck load of 8.88%.

A comparison of the results of the individual simulation runs showed only minimal differences. Therefore, no confidence levels were given in the results.

Previous studies which used discrete-event simulation on supply chain level investigated different machine setups to find the most suitable ones. More precisely, they investigated the supply costs dependent on the transportation distance and number of trucks. Zamora-Cristales et al (2013) found maximum differences of 14% between best and worst setup regarding the number and load capacity of trucks. Asikainen (1995) investigated a supply chain crushing stumps at the roadside. The maximum difference between the best (3 chip trucks) and the worst (1 chip truck) setup was 56% in total supply costs at a transportation distance of 140 km. When comparing the best (2 chip trucks) and the second best setup (3 chip trucks), the difference still amounted to up to 30% (80 km transportation distance). In a later study, Asikainen (2010) again investigated a supply chain for crushing stumps at the roadside. At a transportation distance of 120 km the total costs per MWh differed by as much as 92% between a 1-truck and a 4-truck setup. The maximum difference between the best (2 trucks) and second best (3 trucks) setup was still 25% at a transportation distance of 20 km. These results demonstrate the large improvement potential which lies with using the best machine setup. In Paper III a cost reduction of up to 7% was achieved. This seems to be a rather low percentage compared with previous studies. However, the study did not strive for finding the best supply chain setup. In fact the supply chain setup was unfavorable in certain conditions, for example when transportation distances were long. The expert interviews showed that the setup with two chip trucks was typical for the investigated case, independently of transportation distances. The reason given by the interviewees was that in particular in Peak period, when the fleet available in the region works to full capacity, hiring additional trucks and drivers is difficult. This statement proves the importance of improving the raw material process enabling existing supply chains to increase their productivity. This aim was achieved with an increase of up to 29% on average in Peak period.

The increase of efficiency during peak periods leads to a trade-off. During Interim 1 and the Summer period, low ranking storages are supplied which means the efficiency of the supply chain is low. However, this could easily be compensated. In these periods availability of fleet capacity is no issue, meaning lower efficiency can be compensated by working longer hours.

In contrast to the papers I to III, paper VI investigated the effects of process improvement measures in practice by analyzing the cost-benefit ratio of improving information logistics through ICT in forest biomass supply chains. Even though, the working time savings claimed by FOA2 seem to be very high considering the comparatively low annual volume supplied by them, the study succeeded in showing the saving potential of applying the SCM tool for forest biomass supply. Proving these high estimations would require a detailed investigation of the case. The results of the study are in line with earlier results from industrial roundwood procurement operations. Linnainmaa et al (1996) investigated the EPO wood procurement management system of Stora Enso. In these large-scale procurement operations they estimated the saving potential to be at least several million USD. Bodelschwingh (2006) applied BPR together with ICT and, besides the saving potential through streamlining business processes, found that improving information logistics could cut the pass through times by one third. In Switzerland the SCM tool Polver was investigated. The results showed that the tool provides potential savings of working time of 40% (Lemm et al 2006). These studies investigated SCM tools in roundwood operations where work steps differ considerably from forest biomass operations. For this reason, the results are not directly comparable to forest biomass to energy supply chains. Nonetheless, they set a trend by proving an increment of efficiency through ICT in forest supply chains and hence confirm the results of Paper IV.

It should be noted that the study only covered the saving potentials of the FOAs. The benefits of the contractors could not be assessed. Sikanen et al (2005) investigated the Finnish fleet management tool Arbonaut Fleet Manager and found a saving potential of 100–140 USD per month. However, the focus of their study was not cost-benefit or profitability analysis. Sikanen et al (2005) indicate that potential savings are most likely higher, and a full assessment would need a more detailed study. Furthermore, the system Sikanen et al (2005) studied was developed few years earlier and differed from the one investigated in paper VI. The development of ICT during the last ten years has been tremendous and modern systems are more functional and reliable. Nonetheless, the need for and the benefits of ICT for forest biomass supply have been recognized at least by big players in the field (Lahti and de Bie 2013) who know about the importance of careful planning and management of the whole supply chain.

Even though, BPR and ICT were investigated separately in this thesis, improving information logistics through ICT is an important enabler in BPR (Grover and Malhotra 1997) and both go hand in hand preferably. This becomes evident when having a look at the BPR measures applied in article II. Empowerment requires that the people who make the decisions are enabled to make them on a sound basis, meaning valid and reliable data and information. Task elimination requires that FUs share information so that others do not perform tasks like stand assessment redundantly. The measures contact reduction, standardize data exchange and digitalize data exchange essentially are core tasks of ICT.

5 FUTURE RESEARCH NEEDS

Papers I and II demonstrated the need for improving the efficiency of business processes in small and medium-scale forest biomass to energy supply chains but only a few suggestions were implemented in the focal supply chain. Future research should investigate how to implement improved business processes under consideration of the sociopolitical dimension. In particular it should be investigated how to overcome social obstacles.

More case studies on the topic are required. Comparing a number of case studies in similar and different working environments may help to identify general problems in the organizational structure of forest biomass supply chain. Based on that, guidelines and tools can be developed. This would help existing supply chains to improve their operations and others to get it right from the start.

Especially from a perspective of technology and know-how transfer, the analysis of business processes is interesting. This may facilitate transferring not only productive machinery. It may also help to establish supply systems in countries where wood-based energy is a rather immature branch of business. Countries like Finland and Sweden could, besides productive machinery, transfer proven supply systems. That requires a thorough understanding of how the organizational setup works in its respective working environment, in the first place. Secondly, it facilitates the analysis of the working environment the system should be transferred to. Finally it enables one to adapt the system to the given working environment. Through this kind of approach, countries could benefit from the development; for example Sweden has experienced this over a period of 30 years (Junginger et al 2005).

The present study investigated BPR and ICT separately for the mentioned reasons. In future studies, BPR should be applied using ICT as an enabler so that the full benefits of combining both can be investigated. Earlier studies largely focused on the benefits FOAs and forest service providers may gain from ICT. However, for ICT to work, for example in the form of SCM applications, all actors in the supply chain must apply it and feed the system with required information. Contractors are reluctant to invest in these systems due to a lack of visibility of the benefits. It should be researched to what extend contractors benefit from ICT. In particular under the constraint that in small and medium scaled forest supply chains many contractors only do a share of their business with the supply chain using the application. Furthermore, it should be investigated if there is need for a more contractor-centered perspective in the development of ICT. It is to be expected that contractors are more likely to use ICT if it convincingly serves their own needs.

ICT and more sophisticated SCM systems require standardized data to work reliably. This standardization should be done internationally. The StanForD –standard is already used in roundwood procurement and corresponding systems should be created also for energy wood business.

Paper IV demonstrated how an information-based raw material allocation process can increase the cost-efficiency and productivity of a forest biomass supply chain. Putting this process into practice most likely requires changes to underlying business processes such as the purchasing of raw materials and order assignment to contractors. It ought to be investigated how these business processes work at the moment, which changes are required and how these changes can be implemented for the raw material allocation process suggested in Paper VI to work successfully.

The study used drying curves by Sikanen et al (2013) which were assumed to be valid for all storages. However, the drying behavior of the single storages depends on the particular climate conditions and other factors like ventilation and exposure to the sun of the storage place (Nurmi 2007). Currently, more sophisticated drying models are being developed which take such factors into account, allowing for a more exact prediction for single storages. Moisture content affects dry matter losses in energy wood storages (Dix and Webster 1995) and have been found to be significant, in particular in logging residue storages at the roadside (Filbakk et al 2011). Dry matter losses have a notable effect on the economy of operations (Acuna et al 2012). Once more precise models are available, subsequent studies should investigate their potential for improving the productivity and economy of forest biomass supply chains. A promising approach for simulating more complex behavior regarding drying and raw material losses dependent on storing conditions is agent-based simulation. Here the storages can be modelled as agents with individual behavior according to the conditions in varying storage locations.

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