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Added-value innovation of forest biomass supply chains

Kalle Karttunen

Department of Forest Sciences
Faculty of Agriculture and Forestry
University of Helsinki

Academic dissertation

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Author: Kalle Karttunen

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Thesis Supervisors:
Professor Lauri Valsta
Department of Forest Sciences, University of Helsinki, Finland

Professor Bo Dahlin
Department of Forest Sciences, University of Helsinki, Finland

Professor Tapio Ranta
Department of Energy, Lappeenranta University of Technology, Finland

Pre-examiners:
Professor Tomas Nordfjell
Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden

Docent Anssi Ahtikoski, D.Sc. (For.)
Natural Resources Institute Finland, Oulu, Finland

Opponent:
Lauri Sikanen, D.Sc. (For.)
Natural Resources Institute Finland, Joensuu, Finland

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ABSTRACT

The aim of this work was to study how process innovation can be applied in forest biomass supply chains for reducing costs to add value compared to traditional supply chains. The work consisted of four articles using alternative data and a variety of methods.

The process innovation of forest biomass supply chains contains several possibilities. There is a need to identify which processes should be renewed incrementally or completely. The main innovation types determined by the case articles were divided into incremental, radical and network innovation. Achieving cost reduction was possible by innovating traditional forest biomass supply chain processes in a novel way in all cases. The case of network innovation however, presenting the co-operation of an entire supply chain with stakeholders by linking forest management and logistics business systems together in process innovation, provided the highest cost reduction, which can be seen as added value. This is because network innovation includes several structural holes with close connections between processes and systems that offer the possibility of finding more cost reduction potential for the entire supply chain.

The main conclusion of this work is that it is not worth implementing innovation solely inside a company´s own activities, but opening the innovation process for the whole network of a supply chain is crucial. The methods presented in this work could be mainly applied in forest biomass supply chain innovation. The work enhanced the knowledge of innovation usage for forest biomass supply chains.

Keywords: Innovation, strategy, supply chains, forest management, forest biomass

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I am pleased to have had the opportunity to work with high professional researchers during the projects, Jarno Föhr, Olli-Jussi Korpinen, Tuuli Laitinen and Lauri Lättilä from LUT, who earn great thanks. Researchers from Metla Joensuu have participated in the co-operation, thanks to Kari Väätäinen, Juha Laitila and Antti Asikainen. I wish to thank Sinikka Mynttinen from Aalto University for co-operating in the studies. The reviewers of this work did such a good job, a great thanks to Anssi Ahtikoski and Tomas Nordfjell.

I wish to dedicate this work to my lovely family, my wife Inna, and children Juuli and Kosti, who are the joy of my life. A great thanks to my mother, father, sister and brother. I am also thankful for my other family members who worked as a support network.

LIST OF ORIGINAL ARTICLES

This dissertation consists of a summary and four following articles, which are referred to with Roman numerals I–IV. Articles I, II and III are reprints of previously published articles reprinted here with the permission of the publisher. Article IV is the author´s version of the submitted manuscript.

I Karttunen K., Väätäinen K., Asikainen A., Ranta T. (2012). The operational efficiency of waterway transport of forest chips on Finland's Lake Saimaa. Silva Fennica 46(3): 395–413.
http://dx.doi.org/10.14214/sf.49

II Karttunen K., Lättilä L., Korpinen O.-J., Ranta T. (2013). Cost-efficiency of inter modal container supply chain for forest chips. Silva Fennica vol. 47 no. 4 article id 1047. 24 p.
http://dx.doi.org/10.14214/sf.1047

III Mynttinen S., Karttunen K., Ranta T. (2013). Non-industrial private forest owners' willingness to supply forest-based energy wood in the South Savo region in Finland. Scandinavian Journal of Forest Research. Volume 29, Issue 1, 2014.
http://dx.doi.org/10.1080/02827581.2013.856935

IV Karttunen K., Laitila J. Forest management regime options for integrated small diameter wood harvesting and supply chain from young Scots pine (Pinus Sylvestris L) stands. Manuscript.

Authors` contributions

Kalle Karttunen was the main author for data analyses and writing for articles I, II and IV. Sinikka Mynttinen was the main author in charge of performing the interviews and mainly responsible for the writing process in article III. All articles were produced according to the project work. Articles I and II were produced in projects organised by the Lappeenranta University of Technology (LUT). Article III was produced in co-operation with Aalto University and LUT. Article IV resulted from a joint project by the University of Helsinki and the Technical Research Centre of Finland (VTT). Logistic simulation models were designed during project work together with Kari Väätäinen (article I) and Lauri Lättilä (article II), who were responsible for simulation model construction. Kalle Karttunen was responsible for forest growth simulations in article IV. The main author was responsible for measuring the productivity and cost analysis in I and II, but Juha Laitila was responsible for the logistics analysis in article IV. Olli-Jussi Korpinen was responsible for the biomass availability analysis in article II. Kalle Karttunen was the main innovation process designer utilising a variety of methods. The work is based on project knowledge and further on the published or submitted academic articles, which are the results of extensive co-operation.

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1 INTRODUCTION

1.2 Background of the work

Climate change, oil resource exhaustion, and the desire for self-sufficiency in energy supplies are driving forces leading towards increasing the share of renewables in energy production (Nabuurs et al. 2007). The balance between economic growth, environmental protection and social aspects for satisfying human need can be seen as an approach of the entire value systems for natural resources (Päivinen et al. 2012). Forest biomass can be used as a substitute for fossil fuels, and its use has several positive effects on national and regional development, such as added economic growth through business earnings and employment, import substitution with direct and indirect effects on Gross Domestic Product (GDP) and balance of trade, contribution to local and national energy security and support for traditional industries (Nabuurs et al. 2007; Renewable Energy Technology… 2007). Increasing energy self-sufficiency by utilising renewable energy, e.g. forest-based energy could be one main objective when striving for economical, ecological and social sustainability.

Targets for the increased use of renewable energy sources in the European Union (EU) are ambitious, aiming to reach 20% of the total energy consumption by 2020 in the EU as a whole (Renewable Energy Technology… 2007). The corresponding figure for Finland is 38% (Pitkän aikavälin… 2008). Biomass currently accounts for approximately 66% of the renewable energy source contribution in the EU (Renewable Energy Technology…2007). Forest-derived fuel plays a major part in the supply of biomass for energy in the EU. National and regional site-dependent features must be taken into account and incorporated into decision-making when building up a future bio-based economy. Forest-based opportunities for energy purposes are promising especially in Finland, which is situated in the northern boreal forest zone and is one of the world’s most heavily forested countries with forest coverage of 73% (United Nations 2012), with forests being the country´s largest source of renewable energy. Alongside industrial roundwood utilisation, recent years have seen the increased use of forest-based energy, particularly untreated chips directly from the forest (i.e. forest chips). This business area exhibits great potential for sustainable growth.

The Finnish forest industry is currently facing problems in many of its core areas: the weakening of export markets as a result of the global economic depression, structural changes in communication paper markets and increasing competition in the supply of paper and board products (Hetemäki and Hänninen 2009). Ecological changes resulting from climate change induced by greenhouse gas emissions pose a further long-term threat (IPCC 2007) in addition to the current economic problems. Bioenergy will foreseeably play a key-role in reducing global greenhouse gas emissions in the long-term (Chum et al. 2011), and the increased use of bioenergy creates opportunities for sustainably managed forests. Greater utilisation of forest-based biomass for energy production may offer business opportunities not only for international forest and energy companies but also for local logistics companies and forest owners. Innovations are needed for either creating new products or services, or for developing novel processes aiming for a sustainable bioeconomy.

Creating and sustaining competitive advantages depends on understanding not only the value chain of one particular business unit but also how units fit the overall value system together with all the stakeholders (Porter 1985). A value chain has originally been understood to include the unit activities of a company. When a company´s supply chain system has enlarged to include other stakeholders, the definition of a value system has been used. A value system includes the value chains of a company's supplier, the company itself, the company´s distribution channels and its customers. Further, the expanding concept for a value system is a cluster, which means the companies and institutions that are located in the same geographical area and sector (Porter 1990). Whether it is the value chain of a company, value system of the company and its stakeholders or a cluster including the entire sector, the ability to innovate plays an important role in strategy management.

Process innovation in particular has been the main research and developing area of the forest biomass supply chain systems for energy purposes. The final goal of forest fuel process innovation has been to reduce supply chain costs to be able to compete with other fuels. Forest fuel is produced directly from forest biomass, which is defined as the accumulated above- and belowground mass of the wood, bark and leaves of tree species. Forest biomass utilised for energy purposes can be produced from logging residues, small-diameter energy wood, stumps and rotten wood by chipping or crushing the wood into smaller forest chips. The problem with forest fuels is that although their utilisation benefits the national economy, it has not necessarily been a profitable business for the private sector (Hakkila 2004). A key challenge for forest fuels has been utilising their biomass volumes in an economical way. The availability and supply costs of forest fuels are very sensitive to worksite factors and transport distances (Ranta 2002). The main reason influencing high transport cost is the low energy density of forest fuels.

The most important stakeholders in the forest biomass supply chain as part of the entire value chain system are 1. forest owners, 2. logistic actors and 3. the plant as a final user of forest biomass material. The forest biomass supply chain has been improved and developed with many innovations that have decreased the costs to a reasonable level for achieving the materials used for energy purposes. This analysis has shown that forest fuel costs have decreased with cumulative production and the experience curve concept is suitable for describing this trend (Junginger et al. 2005). Ample indications exist to show that factors such as technological progress and upscaling have led to significant reductions in production costs in the past few decades (Junginger et al. 2005). On the other hand, the growing use of forest biomass has been increasing both the procurement costs and plant prices.

The development of the forest biomass value chain should be seen as integrating the roundwood and energy wood supply chains (Björheden 2000). On the other hand, the overall value chains of forest biomass have not been studied much. Improvements in the productivity of biomass production, harvesting and transport systems are clearly the key to enhancing the bioenergy share of total energy production (Gan and Smith 2006). The overall cost reduction potential is estimated to be up to 25%, mainly due to better technology, improved harvesting techniques and optimised long-distance transportation (Hogan et al. 2010).

A company´s duty is to make profit for its owners by maximising revenues with the lowest costs. The ability to create profit in the long-term can be achieved in the market by aiming for competitive advantage. Three generic strategies exist in the market for companies to gain such an advantage: cost leadership, differentiation or focusing (Porter 1985). Focusing can be performed either as a cost or differentiation focus, and it seeks to achieve a competitive advantage in its target segments (Porter 1985). It is additionally also possible to achieve a competitive advantage by improving a company´s ability to innovate, which can be accomplished e.g. by increasing its ability to develop products or processes, or create new knowledge (Oslo manual 2005). The goal of innovation is to improve a company´s or its network´s ability to maintain competitiveness by shifting the demand curve of the company´s products (increase quality of product or opening new markets) or shifting the company´s cost curve by reducing unit costs of the supply chain (Oslo manual 2005). The connected relationships between supplier and customer have a strong impact on value creation, in which the supplier needs to offer value to the customer but concurrently needs to gain benefits from the customer (Walter et al. 2001). The shared value concept improves the competitiveness of a company while simultaneously advancing economic and social conditions (Porter and Kramer 2011). Ecological sustainability is additionally one of the most important aspects when utilising natural resources such as forests. Efficient forest resource utilisation should be understood not only as part of general economical, ecological and social sustainability, but also as the networks´ ability to innovate and improve on overall value.

1.2 Forest fuel supply chain

A large number of publications are available in the research of forest fuel systems. Studies can be found that aim at reducing forest fuel costs by the means of forest management (Heikkilä and Siren, 2007; Ahtikoski et al. 2008), harvesting operations (Laitila 2008; Belbo 2011; Petty 2014), efficient transportation (Ranta 2002; Ranta and Rinne 2006; Tahvanainen and Anttila 2011; Laitila and Väätäinen 2012), or power plant prospects (Pihlajamäki and Kivelä 2001). The latter is however seldom presented for forest fuels, but more for wood biomass (McKendry 2002; Baxter 2005). Studies are usually separated to research the perspective of either forest owners, logistics actors or final users. It is difficult to find feasibility studies that include the overall forest biomass value chain, and studies combining two of the previously mentioned systems are seldom presented, not to mention the complete network. A few examples exist of studies combining both forest management and logistics (Ahtikoski et al. 2008; Heikkilä et al. 2009) or logistics and the plant (Jylhä et al. 2010; Jylhä 2011). In recent years research focus of forest biomass supply chains has concentrated on the overall logistics system or a part of the system, e.g. logging, harvesting, chipping or transportation. However, the overall supply chain cost analyses of forest biomass should include costs from the beginning of resource utilisation up to the final users so as to refine new products, services and processes of energy wood biomass in a more economically, ecologically or socially sustainable way in the long-run.

Small-diameter energy wood procurement has been an interesting topic of research and innovation for a long time. Forest management simulation and energy wood procurement have been combined to present a feasibility study method (Ahtikoski et al. 2008; Heikkilä et al. 2009). A study by Ahtikoski et al. (2008) indicated that energy wood harvesting would be reasonable, if boundary conditions are filled, such as energy wood removal, stem size, plant price and subsidies. Heikkilä et al. (2009) showed that the integrated harvesting of industrial and energy wood from dense young stands could be a feasible stand management alternative. While integrated methods for harvesting energy wood and commercial timber have evolved, the high costs compared to those from logging residues have still hindered large-scale utilisation without subsidies (Jylhä 2011; Routa et al. 2013).

The largest share of forest-based chips used in Finland came from small-diameter wood in 2012 (3.6 million m^3). Scots pine represents the largest additional source of small-diameter energy wood (2.5–5.0 million m^3) in Finland (Anttila et al. 2013). It must be noted that the accumulation potential is dependent on the measurement specifications. For comparison, pine pulp wood is the most harvested and used timber assortment in Finland, with a utilisation of 15.9 million m^3 in 2012, which represents 46% of the total pulp wood (36.7 million m^3) and 26% of the total timber use (61.5 million m^3) (Ylitalo 2013).

Optimal forest management by choosing the harvesting time is strongly dependent on wood prices, which are linked not only to the market prices of final wood products but also to the cost structures of production technology and capacity. The combination of natural resources, stands and land, is a composite asset that returns the going interest rate over the chosen exploitation period (Faustmann 1849). The stumpage price paid to forest owners strongly influences the harvesting decisions and profitability of intensively managed forestry. The interest rate used in profitable analysis describes the target return of the forest capital.

Various costing systems have been presented to examine the costs of wood harvesting and supply chains. Therakan et al. (2005) presented an integrated analysis of the economics involved in power generation when cofiring willow biomass feedstock with coal, which can be an economically viable option if the expected overall beneficial effects are accounted for. Puttock (1995) has described marginal and joint costing systems. Marginal costs can be determined by allocating operation costs to the conventional product (such as pulp wood). Joint costing allocates operation costs based on the contribution of each product (Puttock 1995). It is also possible to examine the ability to pay, such as the wood paying capability of a kraft pulp mill (Jylhä et al. 2010). Break-even analyses examine net income delivered to the roadside (Han et al. 2004; Di Fulvio et al. 2011) or by determining supply chain costs among themselves (Laitila et al. 2010; Kärhä 2011). Petty (2014) has presented the cost calculations of small-diameter energy wood supply chains using gross profit margins due to stem size as the difference between plant price and supply chain costs. Stem size at first thinning is caused by the forest management regime, in which tree density after precommercial thinning and the timing of first commercial thinning are the most important factors (Karlsson 2013).

The production costs of primary forest fuel depend on a number of steps within the logistics chain, e.g. harvesting, chipping and transport. The biggest cost difference between logging residues and small-diameter trees has been the cutting share (Hakkila 2004; Laitila 2008). The cost of small-diameter wood has been significantly higher than logging residues during the final felling, which has been an important influence on the large-scale utilisation of forest chips for energy purposes in the early 2000s. The main cost difference between each supply chain operation depends on whether chipping occurs. The chipping system can be executed by the roadside, or at the terminal or plant due to the fragment and chosen logistics of forest biomass (Figure 1). The terminal supply chain is more expensive than other systems (Kanzian et al. 2009), but it is important for the supply security of forest-based biomass.

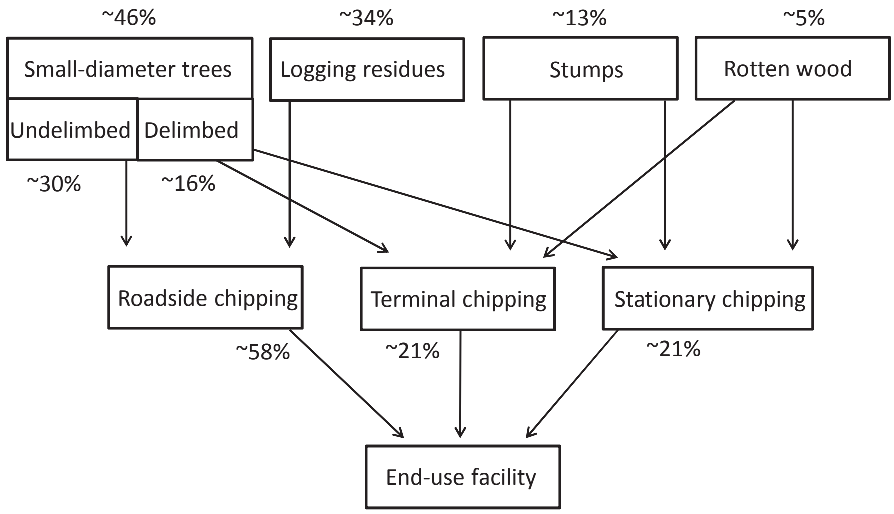

Figure 1. The main streams of alternative forest biomass sources for different chipping methods in Finland in 2012, when total use was 15.2 TWh (7.6 million m³) (Strandström 2013; Ylitalo 2013).

The market supply curve shows how much of a product is supplied at each price level. The price means the monetary value of a commodity, whereas cost means the production value of the commodity. Commodity price theoretically responds to the production costs in a situation where demand and supply are equal. Influencing the price is not possible in a competitive market. An economically reasonable company sets its supply quantity, where marginal cost (MC) is equivalent to the price, which is equivalent to the marginal revenue (MR) (Varian 1987). The smaller the marginal costs of the given amount, the larger the supplied quantity potential of the company. It is significant to understand and point out how the perfect and imperfect markets work in forest biomass supply chains, and how commodity prices and costs are formed in these markets.

1.3 Alternative transportation modes

The choice of forest biomass transportation mode depends on several aspects. Forest biomass demand and supply define the need for long-distance transportation modes. The chipping method defines whether to transport uncomminuted or chipped material. Trucks are the favoured transportation mode in the forest biomass supply chain because of energy purposes. Railway and barge transportation has been used as a part of the forest biomass supply chain in places where terminal facilities already exist. The benefit of water- and railway transport in terms of cost- and energy-efficiency results from their significantly higher load capacity in comparison to truck transport. To be precise, rail- and waterway transportation also include hauling by truck from the forest to the nearest loading terminal. Truck transportation is therefore an essential element of all forest fuel supply systems. Rail and water transport systems additionally require extra loading and unloading, which increase their costs.

The greater the competition and forest fuel consumption of a power plant, the longer the transport distance is. For shorter distances (< 60 km), truck transportation of loose residues and end-facility comminution has hitherto been the most cost-competitive method (Tahvanainen and Anttila 2011), but roadside chipping with chip truck transport has been shown to be more cost-efficient over longer distances (Ranta and Rinne 2006). For even longer distances (135–165 km), depending on the biomass source, train transportation of forest chips can offer the lowest costs when used in conjunction with roadside chipping systems (Tahvanainen and Anttila 2011). The optimum method of transporting forest-based biomass in the most cost-efficient way faces continuous change. The demand of forest fuels for the power plants and current logistical systems has been influenced by supply chain costs and chosen systems.

Transportation unit cost can be decreased by either increasing the quantity of transportation load by developing the efficiency of entire logistics or by decreasing the costs of the utilised machines. The quantity of forest biomass transportation loads is important, because low energy density is one of the main problems in forest transportation, which varies between 0.42 MWh/m^3 (uncomminuted logging residues) and 0.81 MWh/m^3 (chipped forest biomass) depending on the processed biomass material (Ranta and Rinne 2006). Load quantity can be increased by reducing vehicle weight, if it is under a tight legislation limit. Forest biomass supply chains for energy purposes are closely linked to roundwood procurement both in final cuttings (logging residues and stumps) and in integrated cuttings of the first thinning (small-diameter trees) of the entire logistics. Forest management, operational management and long-distance transportation cost savings can be achieved by integrating the biomass supply chain within the roundwood supply chain of forest companies or by using co-operative structures in the biomass feedstock supply, thus increasing overall profitability in the supply chain (Ikonen and Asikainen 2013). On the other hand, the success of integrating roundwood and energy wood procurement is not self-evident (Asikainen 2004). However, traditional roundwood operations must be understood and taken into consideration when new innovation processes of the forest biomass supply chain for energy purposes are planned and determined. The cost comparison of roundwood logistics can be used when developing forest biomass logistics for energy purposes. Unit costs per kilometres (€/m^3 km) can be used to compare unit costs between alternative transportation modes, where costs depend on the quantity and distance of the supply system in relation to the total cost. The train (3.6 cent(€)/m^3 km) and waterway (3.7 cent(€)/m^3 km) transportation sequence have been cost-competitive in comparison to truck transportation (7.5 cent(€)/m^3 km) because of the larger loads and longer distances in relation to low total costs (Metsäteho 2014).

The Lake Saimaa waterways of Eastern Finland provide a fairly good infrastructure (waterways, harbours as terminals and roads next to waterways) for the logistics of forest fuel supply via waterways. However, unless the Lake Saimaa waterways cover all of Eastern Finland, it is a limited transportation method for waterway routes and harbour facilities compared to road transportation possibilities. The railway network and terminals reach all across the country, and they could be used for forest fuel transportation (Ranta et al. 2012). On the other hand, the number of terminals needs to be reduced and efforts should be made for developing their cost-efficiency in several ways; loading track length is one important planning factor for ensuring trains run at full capacity and the capacity and facilities of the terminal storage area are another factor for achieving continuous operations (Iikkanen and Sirkiä 2011). Fast and cost-efficient loading operations are additionally crucial. Distances from forest roads should also be short enough, unless the amount of biomass flowing through the terminal is large enough. Terminals should therefore be situated in areas where forest biomass availability is good.

Several different kinds of forest biomass terminals can be found across the country. Terminals situated a long distance from the end-use facility are called satellite terminals (Karttunen et al. 2008) and ones situated nearby are called feed-in terminals. To fulfill the purposes of supply security, further terminals can act as buffer storages, as enough space is needed for both uncomminuted and comminuted biomass (Ranta et al. 2012). Terminals are mainly owned by companies to maintain supply security, especially during the road-break season for both industrial roundwood and forest fuels. Large-scale demand is the main driver for having satellite terminals, buffer storages or feed-in terminals. Possible investments for the large-scale use of forest fuels in Helsinki, the Finnish capital, include road terminals situated either further away from the end-use facilities to achieve better biomass availability and lower terminal investment costs, or closer to the end-use facilities to achieve lower feed-in costs (Korpinen et al. 2014).

1.4 Demand of forest fuels

Growing forest biomass demand for energy purposes has been the main driver for forest biomass supply chain innovations. As a consequence of national and international targets, policies and activities for boosting biomass energy utilisation, the use of forest fuels has grown rapidly in Finland from the beginning of the last decade. The Finnish national strategy for renewable energy aims to use 13.5 million m^3 (~ 25 TWh) of forest-based chips by 2020 (Finnish Ministry of Employment and the Economy 2010). National raw-material reserves are proposed to enable the reaching of these targets (Laitila et al. 2010).

The current usage of forest fuels is 8.7 million m^3, which was consumed by the heat and power plants (8.0 million m^3) and in small buildings (0.7 million m^3) in 2013 (Torvelainen et al. 2014). Approximately 6.7 million m^3 of firewood is additionally estimated to be used in small fireplaces of single-family homes (Torvelainen 2009). Forest fuel usage has been rapidly growing since the 2000s (Figure 2). Small-diameter trees were the most used forest fuel (3.6 million m^3), whereas 2.8, 1.2 and 0.5 million m^3 of logging residues, stumps and other robust stem wood were used, respectively.

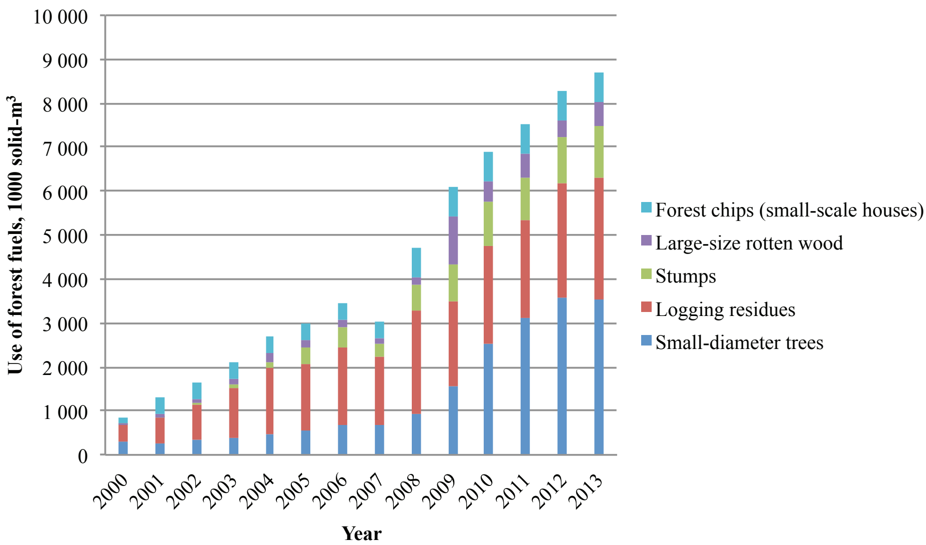

Figure 2. Developing use of forest fuels in Finland, solid-m^3 (2000–2013) (Metinfo 2014)

A total of 376 TWh of primary energy was used in Finland in 2013, of which 92 TWh came from wood fuels (Torvelainen et al. 2014). Wood fuels make up 24% of the total energy production in Finland. Wood fuel consists of the forest industry´s black liquor (54 TWh produced yearly), solid wood fuels in power plants (36 TWh) and small-scale use (18 TWh) (Torvelainen et al. 2014). All forest chips used in Finland in 2013 covered 4.3% of the primary energy usage (16 TWh / 376 TWh).

Demand factors can force companies to improve production and supply processes to reduce costs and lower prices. The market demand curve of forest chips describes the fuel buyers´ willingness to pay for forest chips. The following factors may influence forest chip market prices: the number and volume of users, final product prices and the prices of substitute products or production cost structures. Subsidies for renewable energy or taxes for nonrenewable energy additionally strongly impact market price. The price development of alternative fuels in electricity energy production (taxes not included) is affected by general price developments in market demand (Figure 3).

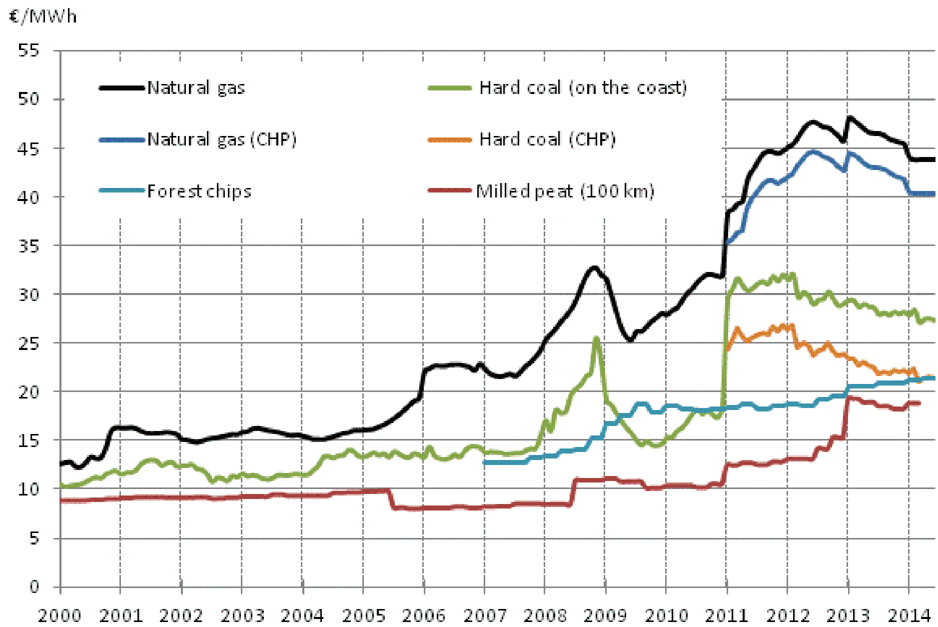

Figure 3. Price development of alternative fuels in energy production for electricity in Finland (Statistics Finland 2014).

Demand defines the products, which can be considered normal, inferior, substitute or complementary commodities. The demand of a normal commodity increases in relation to income, whereas the demand for an inferior commodity decreases (Pekkarinen and Sutela 1996). When the product is a substitute commodity, it functions to replace some other product or it can be replaced by another product in relation to a price change. For example, forest chips can replace coal in heat production, or can be replaced themselves. Complementary commodities are goods, the demand of which will increase when the price of another good is increased (Pekkarinen and Sutela 1996). Forest chips can be a complementary commodity, e.g. when complementing peat in heat production.

Forest biomass used for energy purposes is produced relatively evenly throughout the year, but supply and demand differences do occur, especially in district heat production (Jirjis 1995). Forest biomass supply should be based on customer demand, meaning that it is in greater demand during the winter (Nurmi 1999). In boreal areas where forest chip demand is primarily for heat production, the demand curve strongly correlates with seasonal temperature changes. Biomass supply can be geographically patchy, making it more difficult to secure raw material supplies (Ranta et al. 2005). When the annual consumption of forest chips in a single plant increases from 10 000 m^3 to 100 000 m^3, the mean procurement costs increase by 8–15% (Asikainen et al. 2001). On the other hand, a fixed cost of the entire procurement system may keep total costs at a high level when fuel usage remains lower than the system could enable. Procurement costs remain the major impediment for large-scale biomass when competing with fossil fuels (Gan and Smith 2006). Decreased procurement costs will increase the optimum scale of operations and make new volumes of resources available (Andersson et al. 2002).

2 RESEARCH FRAMEWORK: INNOVATION BUSINESS STRATEGY

2.1 Definition of innovation

The aim of this chapter is to introduce innovation theories as part of business strategies. Innovation is the only way to sustain a company's competitive advantage in the long run (Schumpeter 1934; Rumelt 1984). The main interest is to define the innovation types that can be used for the process innovation of forest biomass supply chains. "The process innovation can be intended to decrease costs of production or delivery, to increase quality, or produce/ deliver new or significantly improved products" (Oslo Manual 2005), meaning reducing the costs and/or increasing the income in a way that produces a more economically favourable outcome than the old way. New innovative supply chain processes are described in this work as a way to decrease delivery costs. Cost reduction is part of the aim for increasing added value in supply chain processes. Analysing process innovation types as part of business strategy management can lead to novel innovations in the forest biomass supply chain for use by a single company, the entire network of stakeholders or overall innovation policy.

"An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations" (Oslo manual 2005). By definition, innovation novelty can mean either new to the company, which is a minimum requirement of innovation, or new to the market or to the world (Oslo manual 2005). Usually innovation novelty is examined from the markets´ and technologies´ point of views (Garcia and Calantone 2002).

"Innovation activities are all scientific, technological, organizational, financial and commercial steps which actually lead to the implementation of innovations" (Oslo Manual 2005). Innovation types can be divided either into product, process, marketing or organisational innovations (Oslo Manual 2005). More than one innovation type can be included in the innovation processes, which may have an important role in company competitiveness and productivity gains.

Process innovation types are studied in this work, meaning the implementation of a new or significantly improved production or delivery method. Process describes an activity managed for transferring inputs into outputs. The output of one process often forms the input of the next one. The aim of the work is to decrease the unit costs of production and/or delivery as a form of forest biomass supply chain management. Organisational innovation means the implementation of a new organisational method in the company´s business practices, workplace organisation or external relations (Oslo Manual 2005). In this work, it is possible to discover links to organisational and product innovation as sub-types of the main innovation processes.

Distinguishing between process and organisational innovations is the borderline case for innovation surveys because both innovation types aim at decreasing costs through new or more efficient production, delivery and internal organisation concepts. There may be mixed aspects of both innovation types. The definition of process innovation describes "the new or significantly improved production or supply methods to decrease unit costs (or increase quality)", whereas the definition of organisational innovation involves "the first use of new organizational methods in the firm´s practices, workplace organization or external relations" (Oslo Manual 2005).

The theory of innovation process has been traditionally linked to a company´s internal processes and innovation has been seen as a closed theoretic-technical process (Lundvall 2007). Market demand is the main factor defining the need for innovation. Innovation combines knowledge, experience and technology in a new way. Traditional business strategies are on the way of becoming more open, especially in the innovation process dealing with co-operation and networking (Chesbrough and Appleyard 2007).

The origin of innovation theories is credited to Joseph Schumpeter, who argued that economic development is driven by innovation (Schumpeter 1934). Innovation is defined as a dynamic process in which technologies replace the old with "creative destruction" either through "radical" innovations creating major revolutionary changes or "incremental" innovations continuously advancing the process of change. He argued (Schumpeter 1934) that technological innovation creates temporary monopolies, allowing abnormal profits that would be competed away by rivals and imitators. Temporary monopolies were necessary to provide the incentive necessary for companies to develop new innovations (Schumpeter 1934).

Innovation can be seen as an aspect of business strategy management that improves efficiency aiming at company growth and success. Repositioning production or output in the value chain may create a competitive advantage in relation to competitors (Sutton 1992; 1998). Improving productivity as process innovation is the way for a company and its network to achieve a cost advantage over its competitors. The main goal is to increase added value to the final customer in the long-term while enabling more profit to the company and its network in the short-term. The current market situation defines how the added value is shared between the customer and a company´s network under a competitive market situation.

The innovation process may be an economical risk for a company because it is not free of charge. According to a study by Heimonen (2012), the innovativeness of small and middle-sized companies decreased profitability in the short-term. Innovativeness may also range between company size. Innovativeness is the ability to identify potential opportunities for changing environments, which creates completely new needs and relation networks (Ruckenstein et al. 2011). It must be noted that innovation processes differ greatly between sectors, e.g. research and development (R&D) recovery capabilities in the high-tech technology sector play a main role in innovation activities (Oslo Manual 2005). The role of R&D and non-R&D inputs are crucial to understand in innovation processes from sector to sector.

Current innovation research has underlined the meaning of learning and spreading know-how instead of theoretic-technical innovations. Co-operative networking can be seen as one of the main innovation process themes nowadays, but far more detailed research needs to be conducted in the form of case studies (Pittaway et al. 2004). The study by Burt (2004) showed that managers whose networks spanned structural holes were more likely to express ideas and discuss them with colleagues. The current concept of innovation is based on social reach, where innovations can normally be produced by co-operating and interacting between companies and alternative stakeholders. The concept of social innovation is focused on alternative modes and a combination of know-how and social capital (Lundvall 2007).

The origin of technological process innovation can be found in business strategy management. In this work three main types of innovation are presented based on "incremental innovation", "radical innovation" and "network innovation" (Table 1). Business strategy management can be divided according to the innovation types either incrementally as "continuous improvement" or radically as "business process re-engineering" or networking as "value network". The concepts of innovation processes will be defined as part of the case studies concerned with forest biomass supply chains.

Table 1. Outline of the main innovation type classification used in this work.

	Incremental innovation[1]	**Radical innovation**[2]	**Network innovation**[3]
Paper	Paper I	Paper II	Paper IV
Business strategy	Continuous improvement[4]	Business process re-engineering[5]	Value network[6]
Innovation type[7]	Process	Process	Process
Innovation sub-type[7]	Organizational	Product	Organisational
Innovation types as strategy	Closed (process)/Open[8] (Organizational)	Open[8] (process)/Closed (product)	Open[8]/Outside[9]
Direction of knowledge flow[10]	Top-down	Bottom-up	Horizontal and vertical
Novelty level of innovation	New (or improved) to the company[11]	New to the market[11]	New to the world[11] (extended)
Speed of innovation	Fast	Moderate	Slow
Risk level of case study	Moderate	High	Mild
Purpose of case study	Cost reduction of long-distance logistics	Cost reduction of large-scale logistics	Added value of entire supply chain

1: Schumpeter (1934)
2: Schumpeter (1934)
3: applied from e.g. Nonaka and Takeuchi (1995); Porter (1998); Chesbrough (2003); Burt (2004); Lundvall (2007); Ruckenstein et al. (2011)
4: e.g. Sugimori et al. (1977); Monden (1983); Hammer (1990); Breyfogle (1999)
5: Davenport and Short (1990); Hammer (1990)
6: e.g. Porter (1985; 1990; 1998); Christensen and Rosenbloom (1995); Chesbrough and Appleyard (2007)
7: Schumpeter (1934), Oslo Manual (2005)
8: Chesbrough (2003)
9: Oslo Manual (2005)
10: Nonaka and Takeuchi (1995)
11: Oslo Manual (2005)

The main difference between innovation creation can be seen as the flowing direction of knowledge (Figure 5). Three knowledge inflows (bottom-up, top-down and middle-up-down as vertical and horizontal) have been presented (Nonaka and Takeuchi 1995; Mom et al. 2007). Knowledge in radical innovation usually moves from the individual to the organisation in a bottom-up manner, in which the individual recognizes the problem or opportunity and begins implementing it in the organisation. Bottom-up innovation originates somewhere deep within a company, and everyone is welcome to participate in the process. Innovators are people who come up with ideas and are willing to go through the process of convincing management of their value. Top-down innovation is the knowledge flow in an innovation process, where the people in power set the targets and objectives and provide funding. The organisation recognizes and identifies the problem or opportunity and controls the staff to achieve its implementation, which is left to the appropriate personnel. In network innovation knowledge moves horizontally through the process, where an interchange of knowledge between different units (activities in a company or alternative business systems in the supply chain or connections of cluster stakeholders) can be connected with each other. The origin of vertical and horizontal knowledge flow has been described as a middle-up-down management model regarding knowledge creation, where the team leaders have been in charge of the innovation implementation within a company (Nonaka and Takeuchi 1995). The novelty value of innovation is divided into the category of a new or significantly improved process to the company, new to the market or new to the world (Oslo Manual 2005) as an extended approach. Innovations can be developed within companies themselves as closed processes, or in co-operation with other business companies or other stakeholders as open processes, or completely outside the company (Oslo Manual 2005).

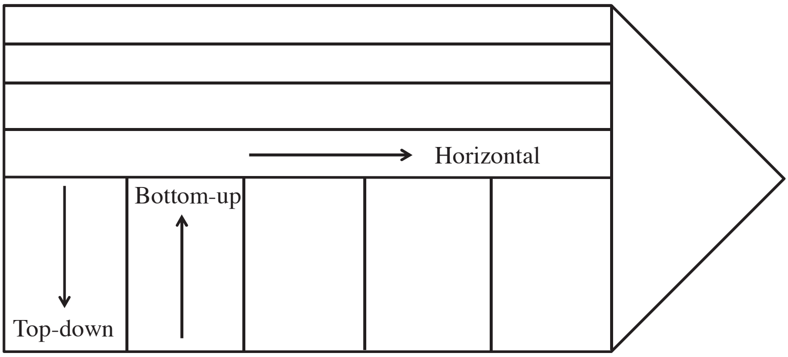

Figure 5. Direction of simplified knowledge flows in a value chain.

Breakthrough innovations have the potential to create markets, shape consumers' preferences, and change consumers' basic behaviour (Zhou et al. 2005), which can significantly influence profitability (Wind and Mahajan 1997). Breakthroughs create something new or satisfy a previously undiscovered need. The role between individual persons or small companies, and cooperation networks is an important starting point for understanding breakthrough innovations. The work of lone individual inventors is highly variable, producing either failures or breakthroughs (Fleming 2012). Revolutionary breakthroughs can provide competitive advantage for small companies (Baumol 2004), which is the reason for taking an interest in innovation. On the other hand, co-operation has a powerful effect on its inventive output and on the opportunities of creating a breakthrough, such as an open innovation strategy for creating new innovations (Chesbrough 2003). Co-operation success is based on a network of individual companies, which must realize how a structure that increases the likelihood of a breakthrough will also disrupt their incremental invention and efficiency (Fleming 2012). Supporting innovation activities and the needs to pay more attention to strategy management is important for enabling breakthroughs in both the private and public sectors (Alasoini et al. 2014).

Regional factors can impact innovativeness, which has increased the interest in regional-based innovation analysis (Oslo Manual 2005). According to the study by Fritsch and Slavtchev (2007), the geographical proximity to particular knowledge sources is important for regional innovative activities. The competitive advantage of a region greatly depends on its networking processes and its ability to create and process knowledge in a rapidly changing environment (Harmaakorpi and Melkas 2005). Location significance is an important part of a company´s strategy because it affects the process costs in many ways, especially the inbound and outbound logistics of a company (Porter, 1985).

2.2 Traditional supply chains

The traditional supply chain means the current system, which has taken the position of the main implementator of the supply chain process in the market. In some studies, this has been called "business as usual" (BAU). In this work, traditional supply chains are presented as a current dominant technology or process of forest biomass supply chains.

Process mapping visualisation was used to define the processes of study objects. Flow charts and process mapping techniques have become important tools for process thinking. Process mapping helps to visualise a process and make it easier to understand the dependencies of horizontal process streams. Process mapping can be seen as the first step in both simulation and innovation process description. Business process mapping combined with simulation methodology has shown its potential for the in-depth analysis of the supply chain in forest business (Windisch et al. 2013a). In this work business process mapping visualisation was used to define the innovation process and its types more clearly of sub-systems, which was divided into 1. the Forest owner, 2. Logistics and 3. the Plant.

The traditional roadside chipping chain of forest biomass was the baseline of the study for forest chip waterway transportation (**Paper I**), whereas the innovation process began from the traditional barge transportation supply chain for roundwood (Figure 6). Traditional roadside chipping and the railway chain were used as a baseline of the solid-frame supply chain concept in the study of intermodal containers (**Paper II**), in which forest biomass availability study methods were used with forest owners willingness to deliver energy wood (**Paper III**) (Figure 7). The traditional supply chain of small-diameter trees (**Paper IV**) is presented in the same figure (Figure 14) as the innovation supply chain case, which presented a denser than normal forest stand density.

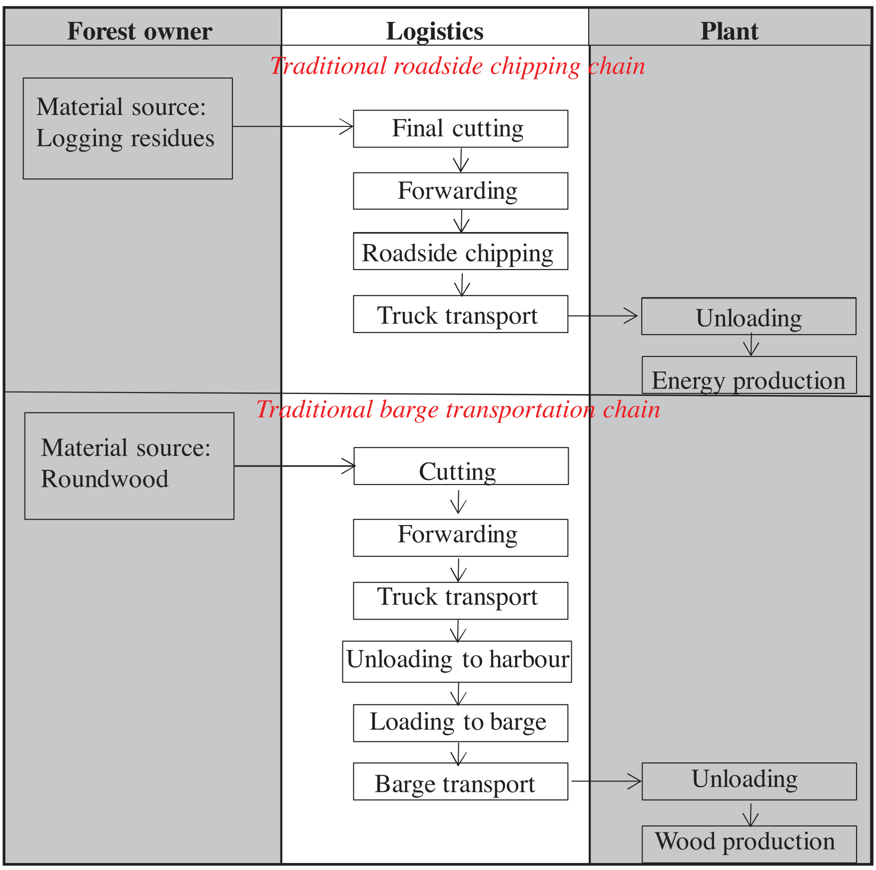

Figure 6. Process map of the traditional roadside chipping chain (baseline) and traditional roundwood barge transportation as a starting point of innovation (Paper I).

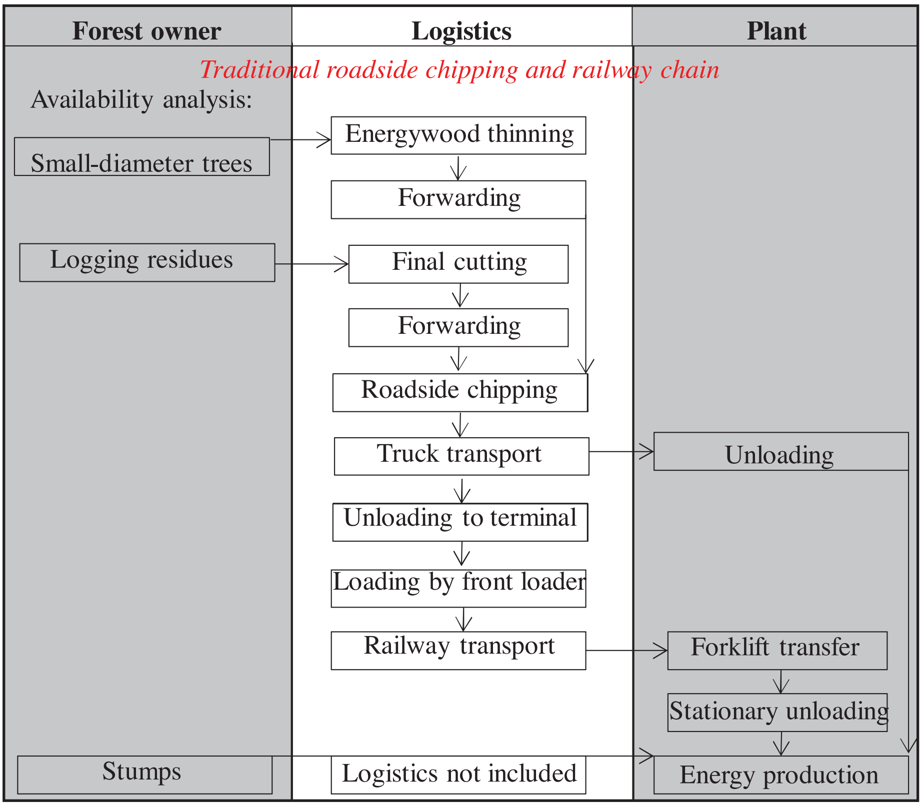

Figure 7. Process map of traditional roadside chipping and railway chain (**Paper II**). Willingness of forest owners to deliver energy wood sources (**Paper III**) is included in the biomass availability analysis.

2.3 Incremental innovation

Incremental innovation is based on the continuous improvement of business strategy management. A huge number of business strategies exist for continuous improvement developed by companies, scientists, consultants etc. The most famous strategies are Just-In-Time (JIT) production (Sugimori et al. 1977; Hall 1987), Lean production (Monden 1983; Krafcik, 1988), Total Quality Management (TQM) (Hammer 1990; Davenport 1993) or Six Sigma (Breyfogle 1999; Harry and Schroeder 2000). Some of these can be seen as a new production philosophy at the beginning of the process and are close to radical process innovation. The change level describes the difference between radical innovation and incremental innovation aiming for continuous improvement. Business strategies for continuous improvement with incremental innovation continue a process chain aiming at either better efficiency, quality or reducing costs. Continuous improvement as incremental innovation can be seen to emphasize small and measurable refinements to an organisation´s current process. The aim of incremental innovation is to slowly improve business processes to maintain a competitive advantage (Figure 8).

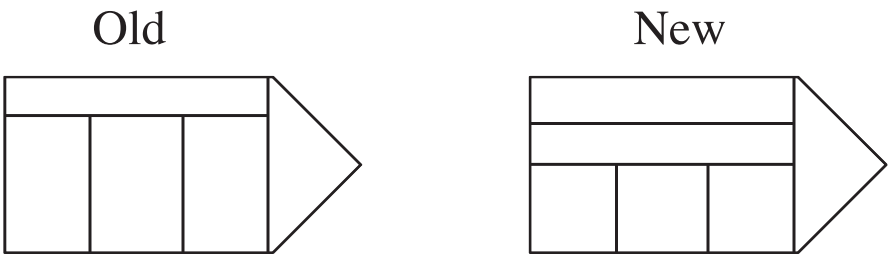

Figure 8. Continuous improvement as incremental innovation for processes means a small change in a company´s chain, e.g. by including an additional horizontal support activity.

Paper I can be considered incremental innovation, which was organised for the current waterway supply chain. The main change was made for the barge transportation of forest chips instead of roundwood transportion. There was a need for replacing fork-buckets used for gathering roundwood with grab buckets to load forest chips in harbour operations. The operation was demonstrated in practice and suitable buckets were changed into the loading machines. A fuel supply system by barge transportation is a complex logistical system including many phases and interactions. A waterway supply chain must be well organised to achieve cost-efficiency compared to the baseline of direct forest chip truck transportation. Even if barge transportation itself is not expensive in long-distance transports, some additional overhead costs may exist, e.g. unexpected fuel supply failures and route problems causing increased expenses. The truck fleet capacity of Finland is high, whereas the number of tugboats and barges used in inland waterways is limited.

A co-operative waterway system was designed as a part of an organisational innovation type to provide the operational efficiency of the barge supply chain. The system is based on the idea of a co-operative control centre, which shares the transportations with the member barge entrepreneurs due to the demand and supply. An opposite system is based on a company-specific model, called the customer-delivery model. Finnish floating waterway operations are organised by operating the forest industry´s control system in practice. The co-operative control system has been studied in roundwood truck transportation (Palander et al. 2006). A similar idea has been presented for use in the railway terminals of forest biomass (Ranta et al. 2014a).

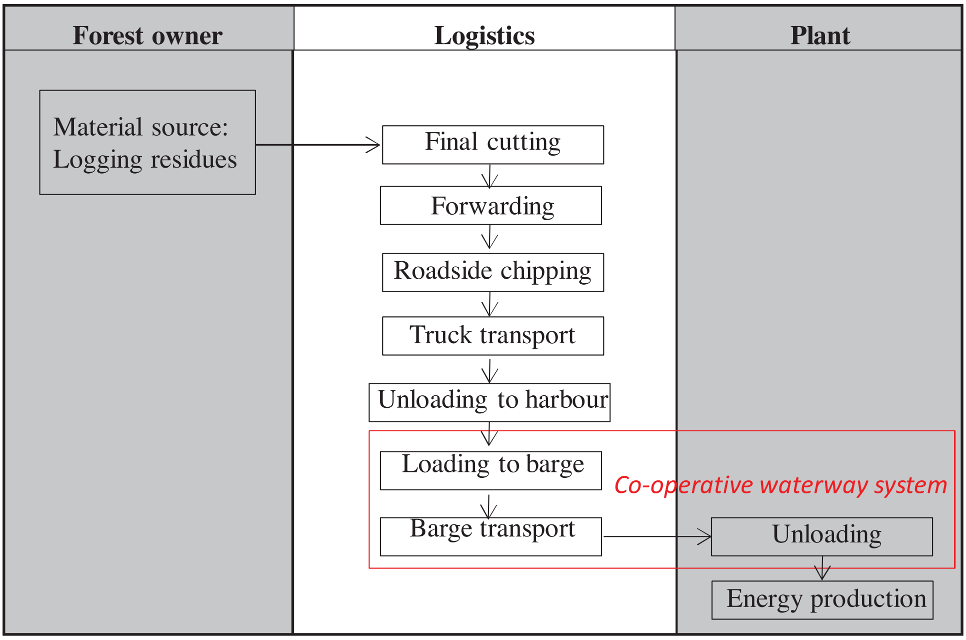

Figure 9. A co-operative waterway system for transporting forest chips was presented as an incremental innovation (**Paper I**).

If forest biomass consumption increases, the use of long-distance transportation would be needed. Larger power plants and biofuel production in biorefineries particularly will require a comprehensive fuel-supply system, including a range of transportation logistics and modes addressing various transport distances for making supply chains more cost-efficient and environmentally friendly. Forest chip waterway transport by barges could be included in the traditional truck-based chip transportation supply chain by using traditional roundwood barge transportation facilities and equipment.

2.4 Radical innovation

Re-engineering is the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements (Hammer and Champy 1993). Business Process Re-engineering outlined a new approach for process management producing radical performance improvements (Davenport and Short 1990; Hammer 1990). The driving forces behind this radical change are an extension of Porter's work on competitive advantage (Porter 1985; Porter 1990), where company growth cannot be simply improved to succeed in a world where customers, competition and change demand flexibility and quick response (O'Neill and Sohal 1999).

Paper II can be seen as an example of radical innovation, where a total supply chain process is reorganised by using new product innovation based on composite intermodal containers for forest chip transportation. Changes are needed in logistics to include more containers, container trucks, container wagons, suitable forklift loaders in terminals and stationary unloading machines in the plant. The handling operations are the main difference between traditional multimodal solid-frame transportation and intermodal container-based transportation. In the container supply chain the container itself is a unit to be shifted, whereas in solid-frame transportation the load must be unloaded and reloaded as forest chips in the terminals. In this study, interchangeable containers were used in the traditional supply chain as opposed to solid-frame railway wagons to be unloaded by forklift loaders in the end-use facility´s terminal. Interchangeable containers are containers that can be used for effective operations between terminals and railway wagons, but intermodal containers can also be transported by trucks. Road transportation dimensions are more limited than in railway transportation.

The idea of innovation was to use a satellite terminal and an intermodal container system as a model to reorganise the truck and railway supply chain of forest chips as an efficient way for supplying the need of large-scale end-use facility (Figure 10). The idea of innovation using containers for the bulk transportation of forest chips is based on the containers being widely used in worldwide trade but they have only a few applications in biomass transportation.

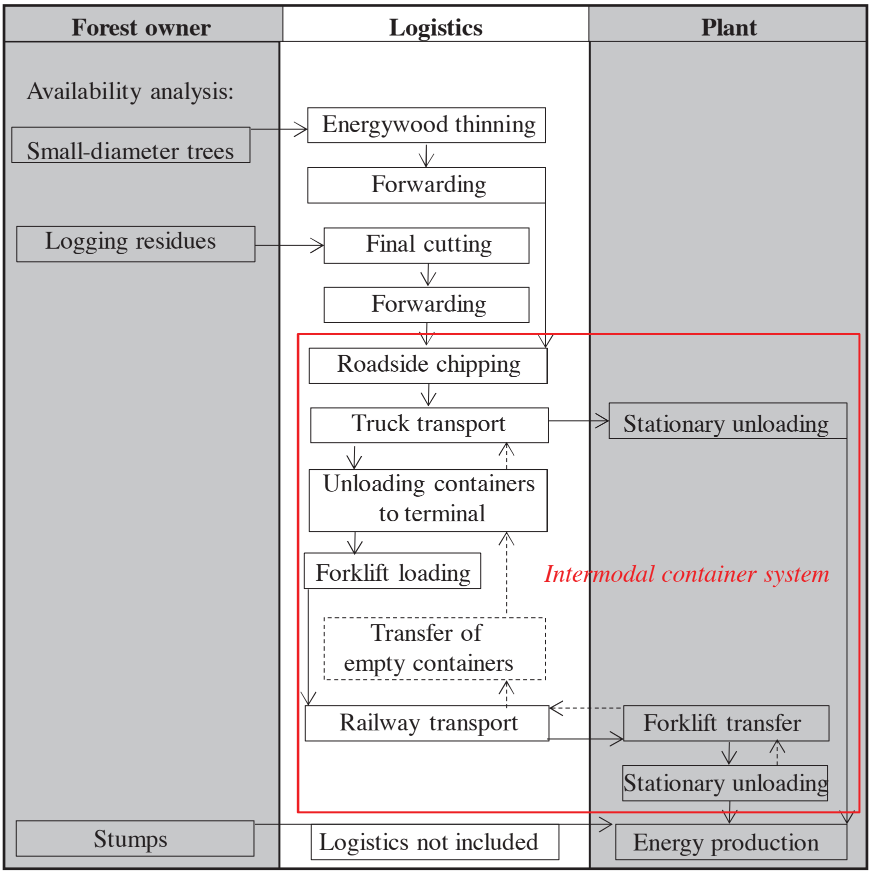

Figure 10. Radical process innovation based on the intermodal container system presented in **Paper II**.

2.5 Network innovation

Porter (1985) created the analysis of competitive strategy and articulated a strategy concept that was rooted in the economics of an industrial organisation. The value chain concept, which defines a value-creation process from raw materials through to the final consumer (Porter 1985) had an enormous influence on both strategy theory and practice. The value chain concept increased understanding of the value creation in a company´s production chain. The company´s competitive advantage is developed in the process activities, which Porter (1985) classified into primary and support activities (Figure 11). In the value chain, a company is not just a system of separate activities, but a system where all activities are dependent on each other. Operations are connected to each other by internal bonds in the value chain. The idea is that the value sum of horizontally managed support activities is larger than the sum of individual vertical primary activities. Added value can be created in either separate activities or in internal bonds between activities.

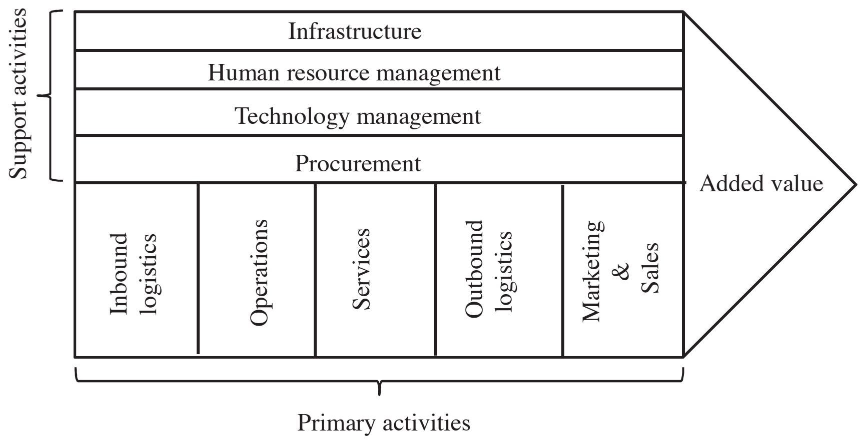

Figure 11. The original value chain concept consists of horizontal support activities and primary activities for organising company operations (modified from Porter 1985).

The value chain has been criticized for focusing mainly on the company itself and not taking into account the potential value of external resources, e.g. innovation communities and surrounding networks, which may represent sources of value creation in an open strategy (Chesbrough and Appleyard 2007). "Open strategy balances the tenets of traditional business strategy with the promise of open innovation" (Chesbrough and Appleyard 2007). "The value network, solving customers' problems, is an important factor affecting whether incumbent or entrant companies will most successfully innovate" (Christensen and Rosenbloom 1995). Criticism may occur towards sustainable issues of the value chain if it only describes a company itself and not the sustainable issues outside.

Harmaakorpi and Melkas (2005) emphasised that the competitive advantage of a region nowadays greatly depends on its networking processes and on the region´s ability to create and process knowledge in a rapidly changing environment. Network connections and structures are more open and dynamic nowadays (Peppard and Rylander 2006). Value creation is a factor affecting every network at the beginning and during development of the process (Kothandaraman and Wilson 2001). The network is an important part of the innovation process where information and ideas are shared with each other indicating innovation creation and development (Malinen and Haahtela 2007). The structural holes between actors in a network are significant in innovation (Burt 2004). The description of innovation creation process consists of a combination of the entire company, market and technology (Figure 12).

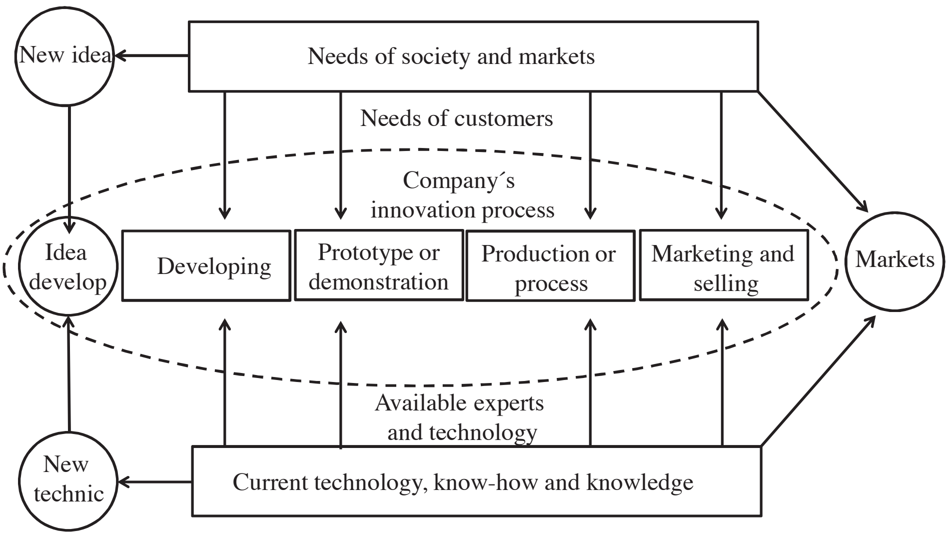

Figure 12. The innovation process consists of a company´s own processes, customer needs, availability of experts and technology and the markets themselves. Original: "Modern coupling model" (modified from Harmaakorpi 2014).

"Innovation co-operation involves active participation in joint innovation projects with other organizations" (Oslo Manual 2005). Organisations can be either other companies or public research institutes. The idea of co-operation is to receive benefits from learning from each other, gaining more knowledge and technology together or creating advantages as economies of scale, which can enable cost reduction or large markets. Social or network capital between co-operators is one of the most important aspects including social trust, values and norms. Social capital, including structural, relational and informational aspects, contributes to the common goals and the adoption of rules (Nahapiet and Ghoshal 1998). In this work we define a methodology for linking more than one cost system together to improve cost reduction (added value) as network innovation. The definition of knowledge flows for the entire forest biomass supply chain process as an old vertical innovation and new horizontal innovation is presented in Figure 13.

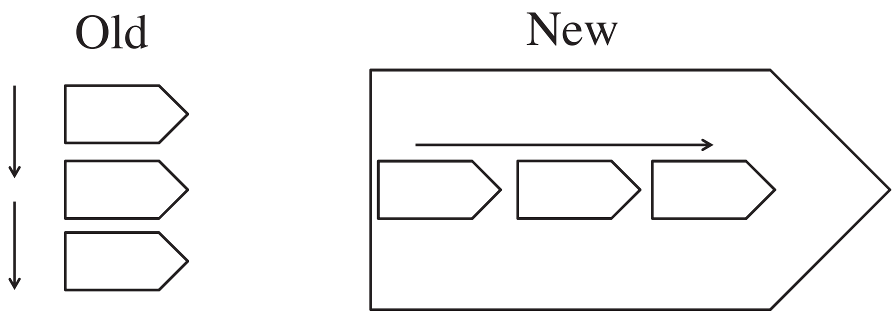

Figure 13. In the old supply chain process knowledge flows between the separate sub-systems in a discontinuous manner, whereas in the new supply chain process it flows horizontally connected inside the common value chain.

Clusters are companies that are concentrated in the same geographical area and operate in the same technological sector (Porter 1990). The main advantage for a company to operate in a cluster is its ability to achieve economies of scale without losing flexibility (Porter 1998). The importance of local stakeholders and innovation success factors in rural areas are based on the ability to contact and create networks over local connections (Suutari and Rantanen 2011). An alternative way of organising a regional innovation policy has been presented for creating innovation platforms, where competitive advantage is based on the ability to recognise business opportunities in the future prospect (Harmaakorpi and Melkas 2012).

Paper IV

The study presented co-operative network process management by linking forest management and logistics together to give customer the choice of either wood production or energy production (Figure 14). The main difference between the supply chains is found in removals and operation functionality: industrial wood must be transported fresh to the end-use facility, whereas energy wood can be dried at the roadside. The entire supply chain must be taken into account when studying the potential added values and choosing the best practices for utilising small-diameter trees. This study contributes to the field by describing and evaluating a potential way of forest resources supplying either industrial wood separately or integrated with energy wood or separate energy wood for energy purposes. Energy wood thinning is a method where forest biomass from an early thinning goes directly to energy production purposes (Karttunen 2006). The first thinning can be applied for energy wood collection if sufficient energy wood biomass is available in addition to industrial wood (Hakkila 2004). Further, if over half of the total accumulation is going to energy purposes, the process can be called energy wood thinning. In practice, energy wood thinning as part of forest management means that a larger than normal number of trees are left to grow after pre-commercial thinning (Siren and Heikkila 2005; Hyvän metsänhoidon… 2006; Äijälä et al. 2014).

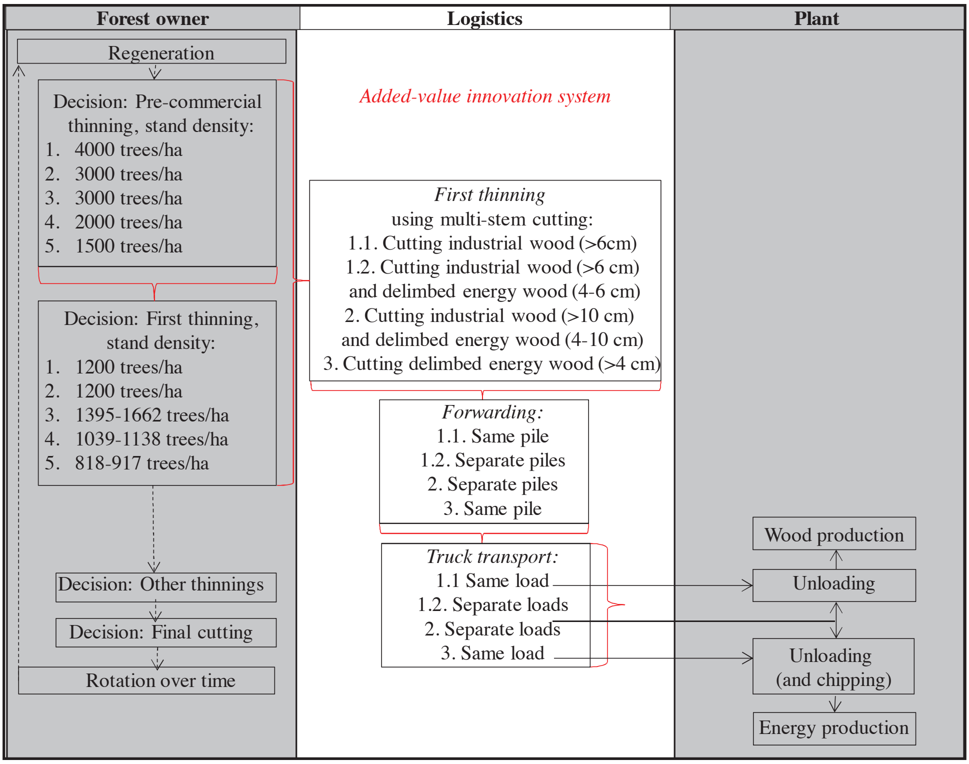

Figure 14. The knowledge gained from each process in each system in network innovation follows from process to process from an added-value innovation system (**Paper IV**).

2.6 Objectives of the work

The objective of this work is to enhance the knowledge concerning the innovation types that are efficient in the forest biomass supply chains. The general assumption is that the implementation process of innovation in the forest biomass supply chain can achieve cost reduction, which can be seen as added value. The research question of this work is: "What kind of innovation types can be used to achieve the added value?"

The idea of the work is to compare the cost reduction potential of alternative innovation types. The work aim was to determine the process innovation types applied in the forest biomass supply chain and to improve potential cost reduction (= added value) compared to traditional supply chains. The aim of innovation is to improve or replace the traditional dominant technology or process. The process implementation can be recommended once the added value advantages of innovation are justified and sufficient. The following study aims were set for the specific articles (later paper):

Article I: Improving the operational efficiency of the barge transportation supply chain for forest chips compared to truck transportation.

Article II: Improving the cost-efficiency of the intermodal container supply chain for forest chips compared to traditional solid-frame transportation solutions.

Article III: Investigating the forest owners´ willingness to supply energy wood.

Article IV: Improving the added-value (=cost reduction) potential of the entire supply chain of small-diameter trees used for industrial and/or energy purposes.

3 MATERIAL AND METHODS

3.1 Method variety

This work is based on input data and a variety of methods for gaining a resulting output cost reduction comparison of process innovation types (Figure 15). The work compares and estimates the innovation types that could be used as part of the innovation strategy for forest biomass supply chains.

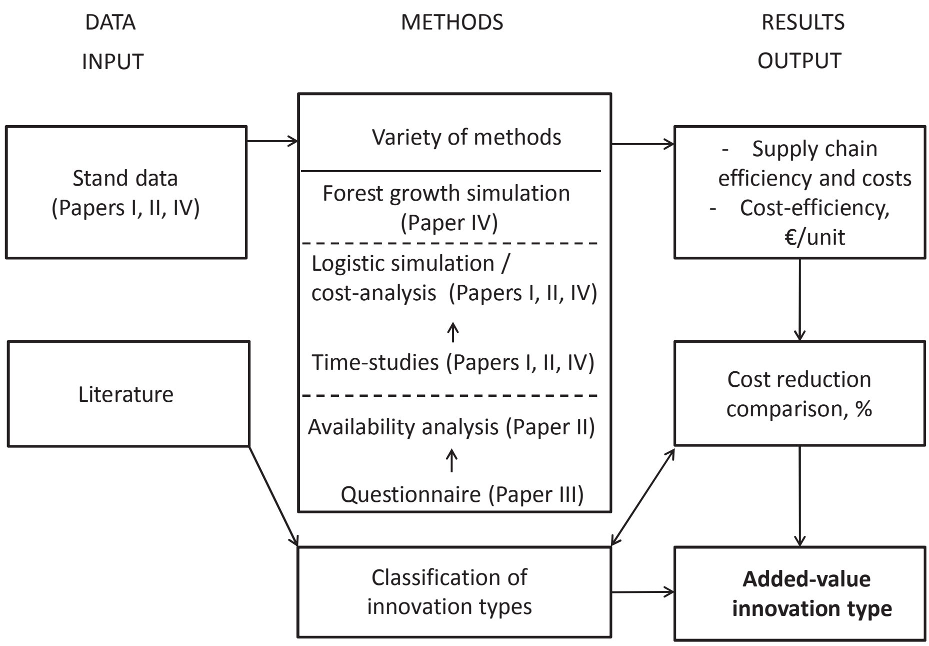

Figure 15. Work outlines consist of data and methods that provide the result for added value innovation type.

The study consists of four publication articles in which varying data and methods have been used. The variety of methodologies used in the work means either variation in the study methods between articles or the use of a variety of methods in specific article. The study results concluded in the articles combined with a literature review of innovation type classification are presented as a conclusion for comparing forest biomass supply chain cases. Cost reduction (%) potential between the traditional and innovation alternative were presented as a summary between the alternative cases (Equation 1).

$$\text{Cost reduction (\%)} = \frac{\text{Cost}_T - \text{Cost}_I}{\text{Cost}_T} * 100 \qquad (1)$$

Cost_T: Cost of traditional supply chain (€/unit)
Cost_I: Cost of innovative supply chain (€/unit)

Supply chain systems involved either large-scale demonstration (**Paper I**), were partly tested (**Paper II**) or based on earlier published productivity and cost analysis (**Paper I, II, IV**). Productivity studies as time studies were used as data for the simulation, which provided results for the annual productivity of the entire systems. Although productivity is an important measure of production efficiency, the costs included in the analysis make it possible to determine the total cost-efficiency of production. When comparing the cost-efficiency of alternative systems, it is important not only to compare productivity but also unit costs (€/unit), which are the result of productivity (unit/h) and operating hour costs (€/h). Cost analyses of alternative machines were used as data for the logistic simulation (**Paper I, II**) or the logistics cost-analyses combined with the forest-growth simulation (**Paper IV**), which presented the use of a variety of methods in specific articles.

Variation in the study methods between **Paper II** and **Paper III** was linked together. The forest biomass availability study included novel GIS techniques in a competitive situation for forest fuels (Korpinen et al. 2012) (**Paper II**) and was helped with information on forest owners´ willingness to deliver energy wood provided by the questionnaire study (**Paper III**). The method was further continued by combining biomass availability analysis and the agent-based simulation study method together (**Paper II**).

The simulation approach

Simulation was used as a summary method for each study case. A simulation model is by definition an imitation of a real system. Models are typically used when it is either impossible or impractical to create experimental conditions in which scientists can directly measure outcomes. A simulation model can be used as an innovation tool to determine alternative scenarios and compare these to a basic system. In process innovation, a basic system usually defines the traditional baseline ("as is" model) and comparison scenarios define the new more innovative systems ("to be" model). The main benefit of simulation is that it allows for the prediction of the effect that changes have on traditional systems and for predicting the performance of a new innovation system under alternative circumstances without interrupting the system in practice. It also makes it possible to manipulate the model in virtual reality giving quantitative results of conditions where new innovation could work in action. Though simulation makes it possible to obtain results from a complex system, it does not itself produce an optimised solution for the problem, but simply runs the model according to the specification given (Robinson 2004). Several scenarios are needed when choosing the most promising alternative. Simulation can be a helpful tool if the innovative alternatives cannot be demonstrated in practice. On the other hand, a simulation can bring with it the benefits of a large number of post-demonstration variations to show conditions in which new innovations can be used effectively and the most promising alternative can be found.

The most used simulation approaches are discrete-event simulation, system dynamics and agent-based modelling. Agent-based modelling can be considered an application of discrete-event simulation. Hybrid models combining two or more approaches in one model can additionally be used. Though many other approaches can be used for understanding system performance in decision-making, simulation is the only one for predicting performance when the models are subject to a significant level of variability (Robinson 2004). Simulation allows users to reflect on the randomness and interdependence of variables in the system (Asikainen 1995). Simulation models can be classified in relation to their use of time and probability functions (Figure 16).

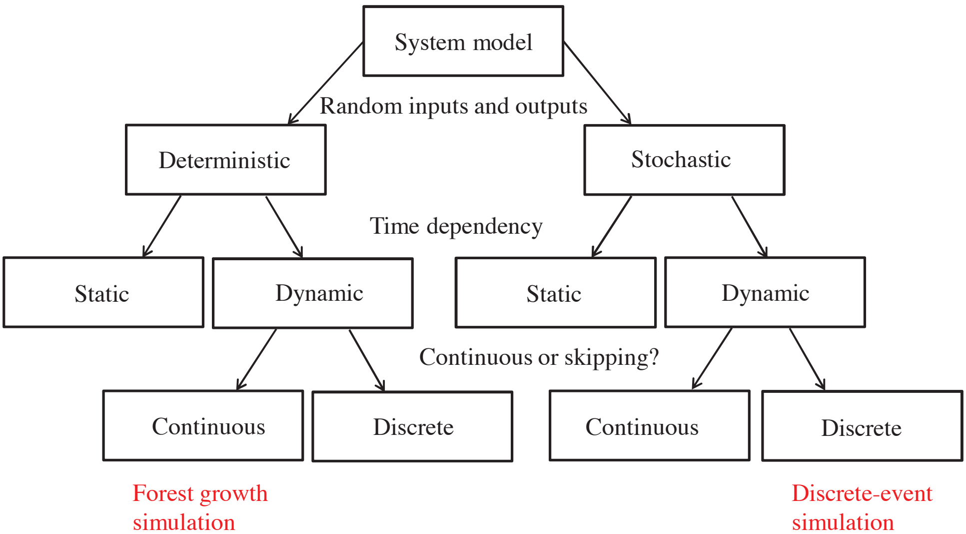

Figure 16. Classification of a system model utilised for the discrete-event and forest growth simulations in this work (modified by Leemis and Park 2004; Manavakun 2014).

A deterministic simulation model does not contain random variables. This means that a certain set of input data will always provide the same set of output during every modelled replication (Asikainen 1995). A stochastic simulation model contains random input variables, which means that output data is not necessarily identical between simulations and it is therefore recommended to repeat simulations several times to calculate the mean value. A static simulation model represents a system at a particular point in time, whereas a dynamic simulation model shows the change occuring in the system with time. The state variables in a continuous simulation change continuously over time. A discrete simulation means that the state variables change only at discrete points in time (Winston 2004). Event points are linked together in chains as time moves forward. The use of discrete-event simulation has been growing in forest biomass supply chain modelling in recent years (Windisch et al. 2013b; Zamora-Cristales et al. 2013; Belbo and Talbot, 2014; Eriksson et al. 2014). The forest biomass supply process chain is a series of work phases, moving forward from one activity to another at discrete points in time. The advantage of the discrete-event simulation method is its possibility to incorporate variations and randomness to produce quantitative output data interlinking dynamic processes with variation.

Discrete-event simulation is the process of codifying the behaviour of a complex system as an ordered chain of well-defined events. In this context, an event comprises a specific change in the system's state at a specific point in time. Clock time is an important part of the simulation. Events occur in the simulation based on a calendar schedule. The simulation follows the calendar schedule and the system will activate the event as soon as the clock time reaches the next active event in the calendar. Usually queues theories with mathematical models are used in discrete-event simulation (Banks et al. 2005). Terms of entity, variables and events are used in simulation model construction. The entity is the object of interest in the system. The entity seizes a resource, which can have several units of capacity that can be changed during a simulation. A variable is a piece of information that reflects some characteristic of the whole system, whereas a collection of variables is called a state that contains all the necessary information to describe the system at any given time. An event changes the state of the system.

Agent-based modelling is the newest simulation approach, which can be described as an application of discrete-event simulation (Lättilä 2012a). Agent-based modelling is possible due to more powerful computers (Macal and North 2005) and it has been the main reason for a growing interest in modelling large-scale systems. Macal and North (2006) have listed some other reasons for interest in agent-based modelling, such as observed systems becoming more complex in terms of interdependence, some systems being too complex to model with other approaches and the organisation of data at finer levels in databases.

Transportation and warehouse modelling can benefit from agent-based modelling principles, when they are becoming too complex to analyse using traditional approaches (Lättilä 2012a). Not many studies exist containing an empirical case that has been simulated and studies are still on the conceptual level. Agent-based modelling has been used in earlier studies also in the context of container management, such as the container terminal system (Henesey et al. 2003; Henesey et al. 2009) and the specific container loading area (Mustafee and Bischoff 2013).

3.2 Productivity analysis

Productivity is the measure of production efficiency. It is the measurement for the relationship between output and input (output/input). In this work the demonstrations were organised to collect productivity data and experience from the supply chain systems. Productivity studies are follow-up studies, e.g. time studies.

Operation productivities were measured using time studies as a follow-up study method, in which the processed forest biomass material (forest chips or small-diameter trees) was the output and the working time the input. The effective working time (E_0) is working time excluding all delays. As normal work always includes short breaks, the gross effective working time (E_{15}) is more precise in describing true work productivity (Uusitalo, 2003). The gross effective working time (E_{15}) includes 15-minute delays or less in duration.

The production time tells time including all delays (Figure 17). Working time further includes repairing time, relocation time and preparing time. Total time is additionally the working time with leisure time incorporated. The following division of working time has been used in mechanised forest work (NSR 1978), which can be applied in other machine productivity studies. The correction factors can be used to estimate the relative proportion of effective working time from the gross effective time or working time in practice (Kuitto et al. 1994).

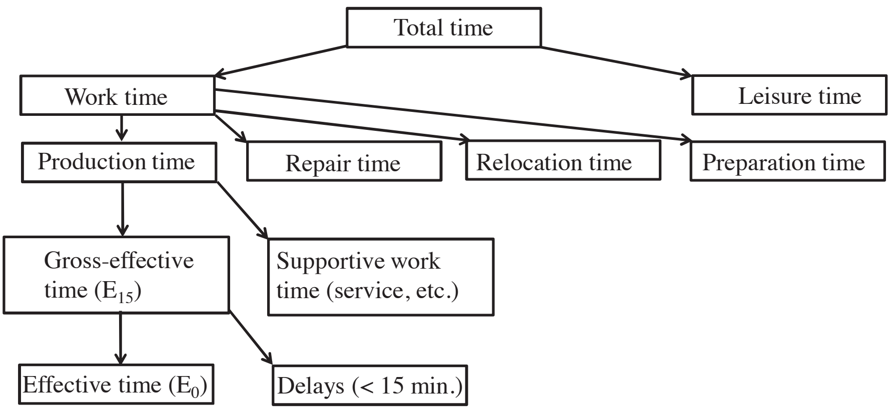

Figure 17. The division of working time as components used in mechanised forest work (NSR 1978).

Paper I: Large-scale demonstrations were organised, collecting time studies and other relevance information, when forest chips were transported for the first time by tugboat and barge in the Lake Saimaa region in Finland. Several kinds of tug boat and barge combinations operate in Finland (Figure 18). The hopper barge used in this study was the Europa IIa, which is most often used in European inland waterway transport. The standard Europa IIa barge's (76.5 m × 11.4 m × 3.7 m) frame load holding capacity was 2650 m^3 (without a ramp). It is possible to pile a load of loose material such as forest chips above the hold capacity level of the hopper barge. A deck barge was used for the small-diameter tree demonstration (Karttunen et al. 2008), but could be modified for transporting forest chips (the case used in the simulation model). Forest chip energy density was one of the interests in the barge demonstration because of the possible compaction effect of a large load and additional mechanical compaction. The speed functions for operating tug boat and a barge unloaded and loaded were adopted from several demonstrations and entrepreneur interviews.

Figure 18. Alternative tugboat and barge combinations in Finland (the systems on the right side were used in the demonstration and simulation) (K.Karttunen).

The productivity of various loading and unloading methods was studied (Figure 19), of which the most suitable and best practices were selected for the simulation model. The time study focused on the lift-on/lift-off (LO/LO) demonstrations, which could be used for the loading of forest chips as well as roundwood, although using different buckets. The gross-effective working times (E_{15}) were measured. Forest chips were gathered from 11 individual forest stands (final felling, logging residues) for each demonstration, with an average moisture content of 39% (range 32–51%). The productivities of two alternative barge supply chains were followed, and productivity information of a company-organised demonstration was also available.

Figure 19. Alternative loading and unloading methods used in the demonstrations (the systems on the right side were used in the time study, cost-analysis and simulation) (K.Karttunen).

Previously gathered time and follow up study information of chip truck transports were used for calculating the consumed time for the transport cycle of the chip truck. Speed functions for driving either unloaded or loaded were adopted from the study by Halonen and Vesisenaho (2002). By using the speed functions, the time durations for driving empty and loaded were derived as a function of driving distance. Terminal time at the loading place by the roadside storage area as well as unloading and auxiliary times were set as constant values added to the cycle time. Terminal times were taken from the publications of Asikainen et al. (2001) and Laitila (2008).

Paper II: Productivity estimates were implemented to all vehicles and machines throughout the supply chain from the roadside to the power plant. The supply chain must include all operations to obtain comparable results between the overall traditional and container logistics. The productivity times and the operating hour productivity coefficients were based on both estimates by the author and on earlier follow-up or pre-test studies (Figure 20). The new approach and large number of alternatives meant that exact productivity information was not always available. Productivity estimates (unit/time) were converted into efficiency figures (time/unit) within minimum to maximum value ranges to be used in the simulation model with either truck or container capacity as the load size. The train was expected to drive both loaded and unloaded for 6 hours one-way (363 km). The speed time of trucks varied according to the type of road in the spatial information. Truck payload varied between the moisture content of forest chips (30–60%).

Figure 20. Container handling operations and pre-tests (all systems were used as the source for simulation) (J.Föhr).

Paper IV: The productivities of the first thinnings were based on the earlier studies (Laitila and Väätäinen 2013, Laitila and Väätäinen 2012, Jylhä et al. 2010, Laitila et al. 2010, Kärhä et al. 2006). The productivity of cutting industrial wood and delimbed stemwood using the multi-tree processing technique was based on the study by Laitila and Väätäinen (2013). In the multi-stem cutting time consumption model, productivity was explained in terms of tree/stem volume (dm^3) and harvesting intensity (number of stems/trees per hectare).

The forwarding productivity of industrial wood and multi-stem delimbed stemwood was calculated using the model of Kärhä et al. (2006) and the above-mentioned timber assortments were forwarded as separate loads. The independent variables calculated in the forwarding were cutting removal (m^3/ha) and forwarding distance (m). The payload of the medium-sized forwarder was set at 9 m^3 for multi-stem delimbed stemwood and 11 m^3 for industrial wood (Jylhä et al. 2010; Laitila et al. 2010; Laitila and Väätäinen 2012). The payload of the medium-sized forwarder was set to 10 m^3 (Scenario 3), when all delimbed stemwood was transported to the same piles.

The effective time (E_0) productivities of cutting and forwarding were converted into gross effective time (E_{15}) productivities using the coefficients 1.393 and 1.302 (Jylhä et al. 2010; Laitila and Väätäinen, 2012). The total length of the strip road network at the stand was assumed to be 600 m/ha, based on an average strip road spacing of 20 m (Niemistö 1992). The forwarding distance was 300 m (e.g. Kärhä et al. 2009; Laitila 2012; Laitila and Väätäinen 2012).

Multi-stem industrial wood and delimbed stemwood were transported using a conventional timber truck with a trailer, assuming a maximum timber volume of 52 m^3, which corresponds to a truck-trailer unit having a 68-tonne legal maximum weight, leaving a maximum payload of 44 tonnes (Korpilahti 2013). The road transportation times were composed of driving with an empty load, driving fully loaded and the terminal times (incl. loading, unloading, waiting and auxiliary time). The time consumption of driving with both a full and an empty load was calculated as a function of transportation distance according to the speed functions of Nurminen and Heinonen (2007).

Truck payload depended on the moisture content, which affected the loading and unloading durations. Both the loading and unloading of timber were performed using the crane of the truck. Tying up the timber load at the roadside and undoing the load at the user site wasted an average 9.9 minutes per truck-trailer unit (Laitila et al. 2009), which was included in the calculation. Auxiliary time (25 minutes per load) was added to the loading and unloading times of timber, corresponding to the time the drivers spent on actions other than actual loading or unloading, e.g. binding and undoing the load, cleaning at the landing or at the delivery point, preparing the trailer and crane, driving at a storage point, turning, waiting, weighing or making arrangements at the delivery point (Laitila et al. 2009; Laitila and Väätäinen 2011).

3.3 Cost analysis

Unit costs (€/unit) can be calculated when hourly cost (€/h) is divided by hourly productivity (unit/h). In the simulation model unit costs are obtained by dividing the year's total cost by the total production volume according to the simulation result. In this work cost-efficiency results as unit costs are presented annually in relation to either long distances (**Paper I**), large-scale forest biomass utilisation (**Paper II**) or stand density before the first thinning (**Paper IV**). Profits are not included in the analysis of different participation methods in the supply chains, but cost reduction potential between the traditional and innovative supply chain can be seen as additional profit (=added value) when the income is the same (profit = income – cost).

The hourly costs (€/h) of machines and vehicles can be calculated when the fixed and variable costs are known. Fixed costs cannot be changed during the short-term (under one year) and these are independent of usability. Variable costs instead vary according to usability. Fixed costs include capital interest expenses and capital depreciation, insurance fees and administration expenses. Variable costs include fuel costs, repairing costs and machine transfers. Labour costs are usually paid as a fixed sum per working hour. Fixed and variable costs together yield the total operating machine costs.

It is normal to perform a cost analysis to calculate the novel price of a machine or vehicle. Novel price includes all necessary additional equipment needed for a working operation. Machine lifespan is dependent on annual usability and machine-specific aspects. The value of a machine decreases annually due to usability (per cents can be used). The machine has a final salvage value after its lifespan is complete. The annual capital depreciation is the result of the novel price minus salvage value divided into holding time as years (Uusitalo 2003), when salvage value can be estimated. Interest can be divided into equity and/or liabilities. Equity is determined due to the alternative investment possibilities. Liabilities are the result of market capital costs. The share of annual costs for interest is calculated using average investment capital (Uusitalo 2003).

The annual time for a machine is an important cost indicator according to the simulation output. It can be divided into effective, relocation and administration time. Working time can be performed in one, two or three (not used) shifts under the working time schedules. It is notable that productivity estimates could lead to inaccurate results when estimating effective time because delays are already included in the simulation model (Manavakun 2014).

Supply chain costs include all parts from the forest to the plant, although depending on the study some operations were included as constant values. These constant values consisted of roadside costs, chipping, road transport costs to the harbour, piling and storage costs at the harbour (**Paper I**), or only roadside costs divided into logging residues and small-diameter trees based on overhead cost, stumpage price, logging cost and forwarding cost (**Paper II**). All cost systems of the supply chain in **Paper IV** varied in relation to the forest stand data. Cost data were either collected from entrepreneurs and experts (**Paper I, II**) and/or from earlier studies (**Paper I, II, IV**) or were based on experienced estimates whenever information was not available. Depending on the paper, costs were analysed closer from the main supply chain item, e.g. waterway supply chain (**Paper I**), or from the entire supply chain, e.g. intermodal container supply chain (**Paper II**), or from linking together forest management and logistics costs (**Paper IV**). Unit costs of €/MWh (**Paper I, II**) or €/m^3 (**Paper IV**) were used depending on the final supplied product either for energy purposes as forest chips, or as delimbed energy wood or industrial wood production as roundwood. Well-known conversion values were used for comparison, which corresponds to the average moisture content of forest biomass (Alakangas 2000).

Paper I: The cost and consumption factors for the vessels, barges and material-handling machines in harbours were either self-reported by the entrepreneurs or surveyed from other sources (Table 2). Costs were booked via a cost-accounting calculator. Run-time costs included capital, labour and fixed overhead costs in addition to operating costs. Fixed costs for the in-port period included capital costs, salaries and other fixed overhead costs. Total unit costs were converted from mass units to energy units (Alakangas 2000).

Table 2. Average annual operation and cost of machines according to the simulation and machine costing models. Prices and costs are presented without value-added tax. (**Paper I**)

Cost element	Purchase price, €	Operating hours / year	Annual cost, €	Hourly cost, €
Small tugboat	900 000	3 642	395 000	108
Big tugboat	3 800 000	2 505	885 000	353
Deck barge	600 000	3 642	51 000	14
Hopper barge	1 000 000	2 505	80 000	32
Modified hopper barge	1 400 000	2 259	110 000	49
Hydraulic boom loader, 67 tonnes	600 000	2 100	200 000	95
Wheeled front loader, 20 tonnes	195 000	2 100	112 000	53
Belt conveyor (30 m)	30 000	2 100	10 000	5
Chip truck (34-tonne payload, 100 km driving distance)	222 000	3 000	198 000	60

The unit cost of waterway transport for forest chips varied with the equipment, operating hours, and water route choices. The time consumption and output figures generated in the simulation were calculated with the aid of cost data received from cost accounting calculators built purposely for each of the separate machines of the device unit. The cost accounting calculator (the Finnish Transport and Logistics association, SKAL) and total time durations of transporting cycle times were used for calculating the unit costs for the chip truck transport of forest chips. Unit costs were expressed as a function of driving distance varying between 50 km and 250 km. The other cost parameters were kept constant before the long-distance transportation of road and waterway transport supply chain scenarios. The loading and unloading operation costs at harbours were taken from the simulation results of the waterway supply chain scenarios, which were based on the special machine cost analysis.

Paper II: The operating costs (excluding Value Added Tax, VAT) of the alternative vehicles and machines were calculated with the aid of machine cost structure analysis (Table 3). Machine cost structure analysis included annual fixed costs (e.g. capital depreciation, interest expenses, insurance fees and administration expenses) and variable operating costs (e.g. labour costs, fuel, repairs, service), which were set as the input values of the simulation model. The purchase prices and annual fixed costs of a solid-frame, i.e., a traditional truck, and a truck with intermodal containers, i.e., a container truck, showed only slight differences and the variable costs of both truck types had the same unit costs, although the final costs varied with distance and net tonnes due to the payload difference of the vehicles. On the other hand, the fixed costs of the container trucks were not included during the July–August season because it was assumed that the container truck would have another use. Instead, the traditional truck did not operate for the same season but still had fixed costs running. The train concepts were used for half a year for biomass transportation and assumed to be fully used for the other half year in both systems.

Table 3. Used purchase price and annual costs of machines and vehicles used in the simulation model. Prices and costs are presented without Value Added Tax (VAT, 0%). (**Paper II**)

Cost element	**Purchased price, €**	**Annual fixed cost, €/a**	**Variable cost, €/unit**
TRUCK TRANSPORT (Scenario 1, 2 and 3)			
Roadside chipper	450 000	285 000	3 €/tn
Container truck	270 000	83 000	0.012 €/tnkm
Unloading machine	85 000	57 519	11.07 €/container
Solid-frame truck	265 000	86 000	0.012 €/tnkm
RAILWAY TRANSPORT (Scenario 3)			
Locomotive and wagons	2 200 000	319 039	
Intermodal composite container	15 000	5 400	0.016 €/tnkm
Metal container	8 390	3 036	0.013 €/tnkm
Front-loader	205 000	154 202	-
Forklift loader	250 000	179 023	-
Unloading machine	85 000	57 519	11.07 €/container

Container lifespan was set to 20 years. The vehicles were given different lifespans: seven years for chippers and trucks and ten for loaders. The calculation system of truck transportation is based on cost-structure parameters received from entrepreneurs, vehicle constructors and SKAL. Train transportation was based on a multimodal system where traditional trucks were used and an intermodal system where container trucks were used. The cost for railroad transport used in this study has originally been calculated from Swedish figures. The calculation tool FLIS, created by Skogforsk, the Forestry Research Institute of Sweden, was used for calculating the cost structures for rail transport.

Paper IV: The hourly cost data of forest machines were taken from the study by Laitila and Väätäinen (2012) and updated to the current cost level using the cost index of forest machinery "MEKKI" produced by Statistics of Finland (2014). The hourly costs for a harvester equipped with multi-tree-handling accessories and a forwarder were 95.4 €/h and 68.9 €/h (VAT 0%), respectively.

The hourly cost data of vehicles and chippers were taken from the study by Laitila and Väätäinen (2012) and updated to the current cost level using the cost index of forest machinery "MEKKI" produced by Statistics of Finland (2014). The hourly cost of the mobile drum chipper was 167.0 €/E_{15}h when operating at a terminal next to a plant. The timber truck's hourly cost was 99.5 €/E_{15}h for driving and 69.9 €/E_{15}h for terminal time.

An entire supply chain cost analysis included the minimum demanded stumpage price, the cutting and forwarding cost of the first thinning removals and logistics costs for the same removals either as industrial or delimbed energy wood. Added value potential of alternative stand scenarios were finally estimated and compared with the baseline.

3.4 Forest biomass availability analysis (Paper II, III)

Questionnaire study (Paper III):
Non-industrial private forest owners (NIPFs) were asked about the conditions in which they were willing to deliver different energy wood types (undelimbed whole trees, delimbed energy wood, logging residues, stumps) based on three alternatives: (1) not willing to deliver at all, (2) willing to deliver against payment but not knowing the correct price to charge or (3) willing to deliver at a desired minimum price. The results for different types of energy wood

were used in one of the data sources in the biomass availability analysis (**Paper II**).

The data set for the study consisted of approximately 30 000 NIPFs, each owning more than 5 ha of forest land in the South Savo region of Finland. The NIPFs in the study own approximately 84% of all forest land area in the region. A sample of 1500 NIPFs was selected from the population using systematic random sampling with regular intervals based on postal codes. The final sample consisted of 382 questionnaires, giving a response rate of 25%.

The data was analysed using the PASW Statistics 18.0 statistical software package. Arithmetic means and distributions were used as univariate statistical techniques in the description of the data. Statistical tests were used to support the interpretation of differences and to assess whether the conclusions can be applied to the survey population. The connections between NIPFs' backgrounds and the realised energy wood supply, intended energy wood sales and willingness to carry out energy wood thinning were analysed by cross-tabulation with a $\chi 2$-test. Only statistically significant results were reported.

Availability analysis (Paper II):
The source data of forest biomass availability consisted of municipal estimates and land-use data (Korpinen et al. 2012). The data was imported to a geographical information system (GIS) environment and processed using ArcGIS software (ESRI 2013).

The points of origin for forest biomass supply were generated via a 4 km × 4 km grid. The midpoints on the grid were extracted for further use in the transport analysis. Raster-to-vector conversion was required to connect forest biomass availability estimates to the transport network in vector format. The biomass volumes of points closer than 4 km to one another were connected.

The results of the availability analysis are given as average amounts of forest chips, including logging residues and small-diameter trees. Stumps were excluded from the study because they are normally chipped at terminal sites, though the influence on demand was estimated. The competitive demand for forest fuels was taken into account as market share analyses (Korpinen et al. 2012). Calculations begin from the theoretic availability of forest biomass sources, in which alternative corrections are performed for achieving more realistic availability results, e.g. technical potential, techno-economic-ecological potential, forest owners´ willingness to deliver energy wood (**Paper III**) or a company´s market share under competition.

3.5 Discrete-event simulation (Paper I)

The discrete-event simulation model was constructed with the WITNESS simulation software, which is designed mainly for the modelling of industrial production systems (Witness 1996). The simulation environment consisted of shipping routes from fuel terminals at harbours to end-use facilities next to cities, and vice versa, in the Lake Saimaa waters (Figure 21). The model furthermore included both the fleet of barges and powered vessels and the fleet of loading and unloading machines in harbours in the system environment. Transportation logistics and interactions before the fuel terminal in the loading phase and after the unloading phase were excluded from the simulation environment.

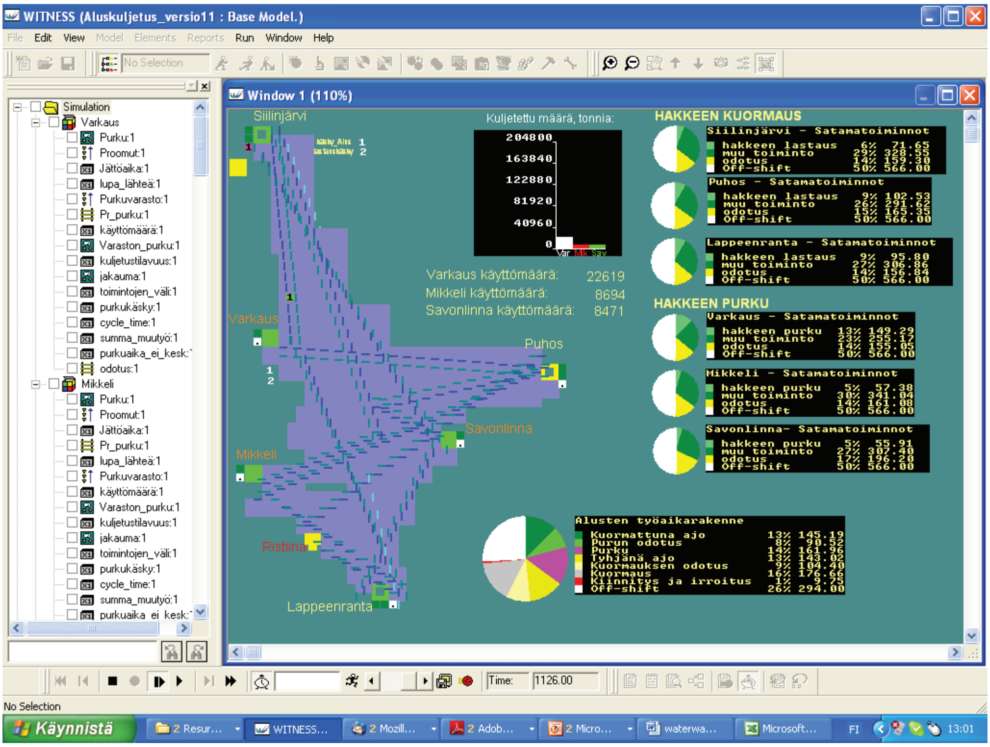

Figure 21. Screenshot of a visualisation sheet in the Witness simulation model (K.Väätäinen).

Three sizes of end-use facilities were chosen for the study provided according to the consumption estimates (%) of forest chips, from the cities of Varkaus (60%), Mikkeli (30%), and Savonlinna (10%) in Eastern Finland. Respectively, three fuel terminals (in Siilinjärvi, Puhos and Lappeenranta) were strategically chosen to meet the fuel demand for the waterway-based supply system from the surrounding areas with good biomass reserves. Distances between loading and unloading terminals ranged from 102 km to 338 km. Fuel-supply terminals were utilised evenly according to the rules of the model, with the assumption that each terminal can supply the same, sufficient quantity of forest chips for the waterway supply system. In the simulation, vessels transported material in one direction only. The routes and directions were fixed for each shipping route from one harbour to another. Shipping unit speeds changed as a function of shipping route characteristics, vessel and barge type, and total barge weight. The operation time per year was set to nine months, excluding the winter months (January–March) during which most waterways in the Lake Saimaa region are closed because of ice cover. The forest chip waterway supply ran day and night all week, 24 hours per day during the active shipping season. For harbour operations the onshore crew worked in shifts from 7 am to 11 pm on weekdays (off-shift during the weekends).

Two main scenarios, with respect to vessel size in use, were set up in the simulation study. The main scenarios were divided into three sub-scenarios addressing i) load size, ii) transport logistics and iii) harbour logistics. Small and large tugboats, with engine power of 350 kW and 750 kW respectively, were used in the simulation model. Two methods were used for loading and unloading operations at fuel terminals. The “load size” scenario contained three load size alternatives for each vessel. The "transport logistics" sub-scenario included three experiments: fixed-barge, interchangeable-barge, and fixed with two barges. The "harbour logistics" scenario included three experiments: shift-dependent, shift-dependent when unloading and shift-independent.

The total number of experiments in the study was 16. Each experiment was repeated five times, and the duration for each replication was nine months. Initial model parameter values were kept constant in each replication, whereas a random number of streams varied between the replications incorporating stochasticity in each simulation run. The results of each experiment were announced as an average of five replications. Though several scenario alternatives were included in the model, the best practices were reported as results in this work.

The results of each experiment replication were different due to the stochasticity in the model. Stochasticity was introduced by the random distribution of certain occurrences or events in the model. The randomised occurrences in the model were the speed correction of the vessel–barge combination, the loading and unloading events and determination of the load size of the barge for each load (Table 4). The load sizes and loading productivities used were based on results from the demonstration studies, in which the average for the material-handling machine used was 177 tonnes/h (E_{15}).

Table 4. Theoretical distributions and their parameters used in the simulation model.

	Distribution	Average, tn/hour	SD	Min. tn/hour	Max. tn/hour
Speed correction	normal	0	0.5		
Load size	normal				
500 tn		500	15		
1 200 tn		1200	30		
1 800 tn		1800	55		
Loading	truncated normal				
Material handling machine		175	10	160	190
Wheeled loader + conveyor		120	10	100	140
Unloading	truncated normal				
Material handling machine		165	10	150	180
Wheeled loader + conveyor		75	10	55	95

3.6 Agent-based simulation (Paper II)

Three main scenarios based on the chosen demand and supply chains for either the traditional or innovative container system were determined (Figure 22). The main scenarios are divided into truck and railway transport options. The first scenario (Scenario 1) involves a comparison between intermodal container logistics and traditional solid-frame truck logistics for the estimated forest chips used in the power plant case (540 GWh). The second scenario (Scenario 2) considers a similar truck transportation but with a higher demand for forest chips and therefore longer distances (740 GWh). The third scenario (Scenario 3) considers the higher demand and longer distances together with the use of a railway supply chain in addition to the truck logistics (540+200 GWh).

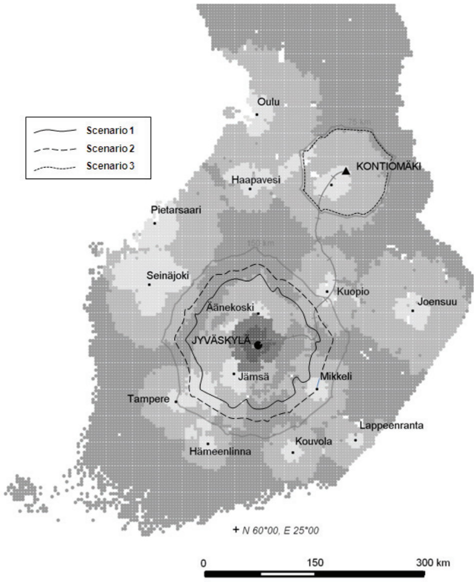

Figure 22. Study area around the city of Jyväskylä (Scenarios 1 & 2) and around the satellite terminal of Kontiomäki (Scenario 3).

The simulation was conducted using AnyLogic 6 software, which is suitable for discrete-event and process-centric modelling (XJ Technologies 2013). The simulation model was constructed through a combination of agent-based modelling and discreteevent simulation. The model consists of a fixed number of truck agents, which follows a discrete-event structure (Lättilä 2012b). The train scenario was additionally created as an agent model but followed the more complex discrete-event structure, including loading and unloading terminals. The model´s user interface was made to aid the understanding and analysis of the study problems (Lättilä 2012b).

Agent-based simulation was chosen so as to ensure adequate versatility, as the trucks need to relatively accurately represent the actual operations to have reliable results (Lättilä 2012b). Each agent gathered information from its local environment and made autonomous decisions. The decisions lead to interaction with other agents and the environment. Each agent has a personal goal that they are trying to achieve. The truck agents have five distinct states: out of service, waiting, moving, being loaded and emptying (Figure 23). The trucks are out of service according to their schedules between the hours of 12:00 midnight and 7:00 a.m. every weekday and are unused during weekends. The trucks operate in two shifts from November until April, and have one shift in May–June and September–October. The trucks do not operate during July–August. The trucks wait at the main terminal of the power plant until they have potential cargo. An alternative number of trucks were used in the simulation scenarios to achieve the demand of forest chips, whereas the number of train agents was kept constant (Table 5).

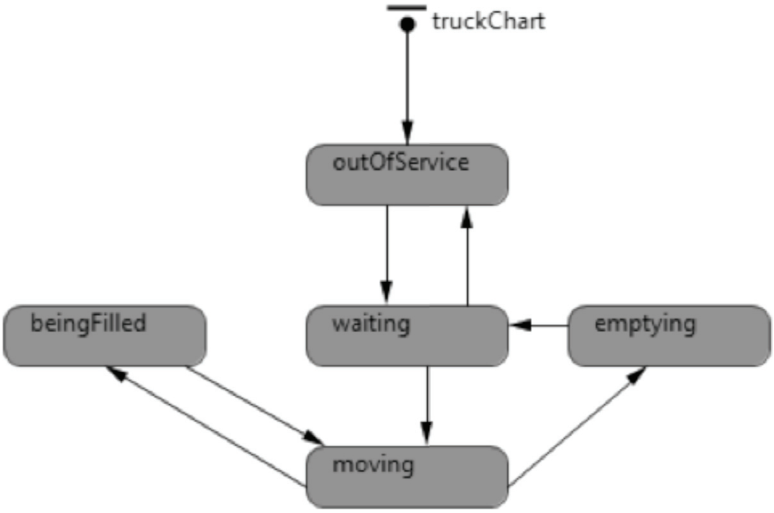

Figure 23. Truck agent used in the simulation (Lättilä 2012b).

Table 5. Number of truck agents used to fulfill the scenario demand targets in the simulation model for the traditional truck (1.1.2, 2.1.2, 3.1.2) and container truck (1.2.2, 2.2.2, 3.2.2) sub-scenarios.

	Scenario 1	Scenario 2	Scenario 3
Traditional truck (number of trucks)	8	14	12
Container truck (number of trucks)	6	10	10

The cargo is generated according to the forest biomass availability analysis. GIS data are used to estimate how long it takes a truck to drive to a potential load. There are 20 potential loads in the model at all times. The model checks beforehand if there is time to pick up and return any of the cargo loads according to the day´s schedule. When appropriate cargo is found, a truck moves to the location. The delay required for the move depends on the distance and type of road between the terminal and the cargo location. When the truck reaches the location, it is loaded. During this time, the weight of the truck increases in accordance to the moisture level of the cargo. The weight of the load mainly depends on the moisture content of the forest chips, and the load is converted from tonnes to megawatt hours using conversion factors (Alakangas 2000). The moisture content of the forest chips ranges between 30% and 60% and is allocated to the simulation model according to the normal distribution for the chosen forest chip source. The moisture content influences the payload of alternative trucks under the weight limit dimension (Figure 24), but has no influence on train wagons. On completion of loading, the truck moves back to the terminal for emptying. The truck is next commanded to seek potential cargo and the route cycles are continued. At the end of the day, the truck returns to the ‘Out of Service’ state.

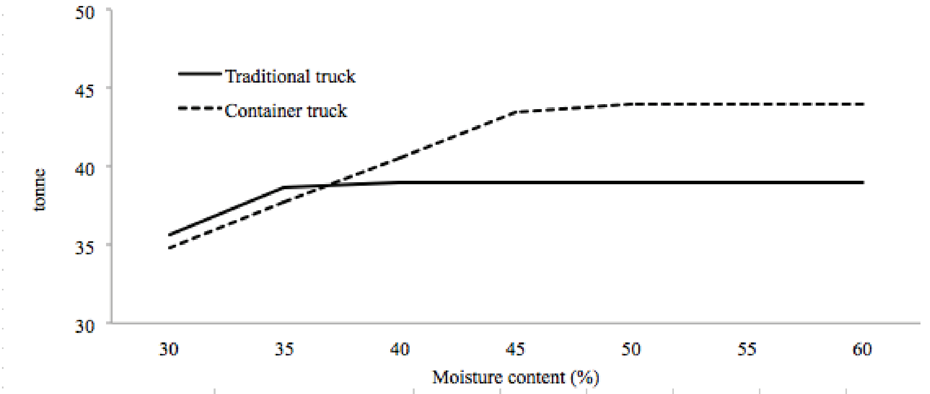

Figure 24. Truck payload according to forest chip moisture content.

Trains are preferred over trucks at the terminal. When a train arrives, the trucks have to wait for the train to be emptied before the unloading machinery begins unloading the trucks. This is due to the stricter time-constraints of the train, which have to follow a specific schedule. Unloading the trains has to be done at night or in the early morning because the container trucks, which were using the same unloading station in the simulation model, began their daily schedule at 7 a.m.

The intermodal composite containers were loaded and unloaded in the simulation model using a forklift loader. The interchangeable containers were loaded with a wheeled front-loader, but unloading was arranged in the same way as the intermodal containers, i.e., using a fork loader and a stationary unloading machine next to the railway line at the power plant. The parameters varied according to the normal distribution in the simulation model (Table 6).

Table 6. Average efficiency (minutes/unit) of loading and unloading (normally distributed) (Scenario. 1, 2 and 3).

	Efficiency, minutes/unit	
Transport option	**Loading** (min-max)	**Unloading** (min-max)
TRUCK TRANSPORT		
Traditional truck		
Scenario 1 and 2	50–80/truck	25–35/truck
Scenario 3 (terminals)	50–80/truck	25–35/truck
Container truck		
Scenario 1 and 2	50–80/truck	8–10/container
Scenario 3 (terminals)	50–80/truck	4–6/container
RAILWAY TRANSPORT		
Intermodal composite container	1–3/container	5–7/container
Metal container	2–3/container	5–7/container

3.7 Forest growth simulation (Paper IV)

This study focused on 24 original stands (+6 estimated stands) representing typical Scots pine (Pinus sylvestris L.) stands in Finland. All stands were pure Scots pine stands based on average regional stand data. Stands represented three temperature sum regions: 900 (Northern), 1100 (Central) and 1300 (Southern) day-degrees (d.d.), and two soil types: the fresh heath MT (Myrtillus) or the dryish heath VT (Vaccinium) site (Cajander 1909). Tree density before the first cutting varied between 1500 and 4000 trees per hectare.

The tree growth of each stand was estimated using the MOTTI stand simulator (Hynynen et al. 2005). MOTTI has been designed to simulate and analyse stand development for alternative forest management regimes in different growth conditions with all major tree species in Finland (Mönkkönen et al. 2014; Hynynen et al. 2005; Hynynen et al. 2014). In this study, the growth of young pure pine stands with alternative growth and density conditions were modelled for the entire rotation. MOTTI version 3.2 (htpp://www.metla.fi/metinfo/motti/) was used in this study based on silvicultural recommendations (Hyvän metsänhoidon… 2006), where thinnings are based on basal area models and rotation period is based on mean diameter or age (Figure 25).

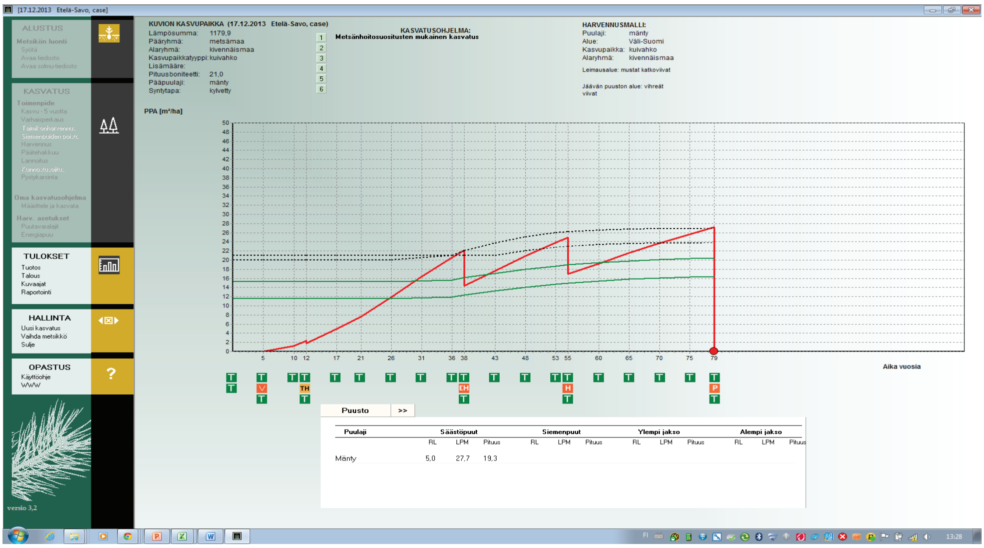

Figure 25. An example of one management schedule simulated by Motti. The vertical axis illustrates basal area (m²/ha), and the horizontal axis presents stand age (years). Dotted lines refer to thinning guidelines, and solid lines determine the basal area recommended after thinning.

Five forest stands and management regimes were numbered and simulated as follows:
1 = 4000 trees/ha: First thinning was performed when the dominant height of trees was set to 12 m and after cutting the number of trees was set to 1200 per hectare. Later growth was automatically simulated according to silvicultural recommendations.
2 = 3000 trees/ha: First thinning was performed when the dominant height of trees was set to 12 m and after cutting the number of trees was set to 1200 per hectare. Later growth was automatically simulated according to silvicultural recommendations.
3 = 3000 trees/ha: Automatically simulated according to silvicultural recommendations. After the first thinning the number of trees varied between 1395 and 1662 trees per hectare.
4 = 2000 trees/ha: Automatically simulated according to silvicultural recommendations. After the first thinning the number of trees varied between 1039 and 1138 trees per hectare.
5 = 1500 trees/ha: Automatically simulated according to silvicultural recommendations. After the first thinning the number of trees varied between 818 and 917 trees per hectare.

A total of 90 separate stand simulations were followed through in this study. Wood weight was assumed to factor variably in alternative scenarios, which may influence transportation payload and costs. The basic density of Scots pine in the first thinning trees was set at 400 kg/m^3 based on the average weight of pine pulp wood chips (406 kg/m^3) (solid) and with the observation that wood procured from a first thinning is 4–9 kg/m^3 lighter (Lindblad and Verkasalo 2001). The average moisture content for small-diameter delimbed energy wood and pulp wood was set at 35% (to be 615 kg/m^3) and 55% (to be 889 kg/m^3) respectively.

Forest management profitability was examined through a comparison of the discounted net value of revenues and costs in regards to the different alternatives (Equation 2). Bare Land Value (BLV) for alternative forest management regimes was calculated, so that the income gained from the first thinning of denser simulated forest management regimes (forest management regimes 1 and 2) was set to give the same bare land value as the baseline (forest management regime 4). The discrete form of Faustman´s rotation model was used and the discount rate was kept constant at 3% (Hyytiäinen and Tahvonen 2001). Trend prices for 2013 were achieved by using real stem prices for an intermediate time period (1995–2012) with an index increase. Costs and roadside prices in the study are expressed in real terms. The real average silvicultural costs in 2012 were used (Metsätilastotiedote 2013). The average unit silvicultural costs assumed were for an MT (baseline) stand, 722 €/ha and 399 €/ha for planting and pre-commercial thinning, respectively. The cost of planting was assumed to be the same for all stands because density after pre-commercial thinning was the starting point for stand data. However, naturally regenerated seedlings were assumed to complete the planted trees. The cost of pre-commercial thinning was assumed to be 25% lower for the denser stands 1, 2 and 3. The average sowing cost for VT stands was 210 €/ha, whereas the other silvicultural costs were the same as presented previously. The cost of soil preparation was the same for all stands: 194 €/ha. Soil preparation and planting/sowing was performed during the first year for all stands. Pre-commercial thinning was carried out either at ages 10 (Southern), 15 (Central) or 20 (Northern).

$$BLV = \frac{\sum_i^t CI_i * (1+r)^{-i} - \sum_i^n SC_{ik} * (1+r)^{-i}}{1 - (1+r)^{-t}} \quad (2)$$

BLV = Bare land value at stand level (forest management no: 1–5), €/ha
CI_i = cutting income at stand age i, €/ha
Thinnings: First, second (all stands) and third thinning (in some stands)
First thinning: First thinning income was set to give the same result as the bare land value of four forest management regimes (Baseline) in stands with one or two forest management regimes
t = Final cutting
SC_{ik} = Silvicultural cost for activity k at stand age i, €/ha
k^1 = cost of forest regeneration (year 0)
k^2 = cost of pre-commercial thinning (year 10 Southern, year 15 Central or year 20 Northern)
n = time of pre-commercial thinning
i = time in years elapsed since the onset of simulation
r = interest rate, 3%

Several scenarios were chosen for supply chain analyses according to the minimum top diameter of wood (Table 7). The minimum length of trees was 3 m. The overall length of long-distance transportation was limited to 100 km. The chipping cost of delimbed stem-wood was not included in the supply chain costs because maintaining comparability of the scenarios for either industrial or energy purposes delivered as trunks to the terminal of end-use facility was important. Costs were presented in relation to stand density (trees per hect-are) before the first thinning as euros per solid cubic metres (€/m^3).

Table 7. Minimum and maximum diameters (cm) of industrial wood (pulp- and logwood) and energy wood in the study scenarios of the first thinning (**Paper IV**)

	Diameter of energy wood		Diameter od pulp wood		Diameter of log wood
Scenario	Min.	Max.	Min.	Max.	Min.
1.1			6	15	15
1.2	4	6	6	15	15
2	4	10	10	15	15
3	4				

4 RESULTS

4.1 Cost-efficiency of forest biomass supply chains

Paper I:
The best supply option in the truck transportation-based supply chain of forest chips (Chip truck 3 000 hours, 34 tonnes) resulted in 9.3 €/MWh and 13.8 €/MWh of supply costs with transport distances of 50 km and 250 km respectively, whereas the best barge transportation supply chain option (Small tugboat, load 1200 tonnes, harbour shift independent) resulted in 10.4 €/MWh and 11.7 €/MWh costs with the same distance comparisons. The best waterway transport scenarios, extracted from both vessel size scenarios, were compared to the truck transportation of forest chips (Figure 26). The forest chip truck supply chain was more cost-competitive than the waterway supply chain at shorter distances and at distances up to 100–150 km, depending on the transport options in comparison. Barge transportation options were more cost-efficient for longer distances. The average of the scale 50–250 km distances was used as a cost-efficient comparison and the result for supply chain innovation cost-efficiency averaged 4.3% (average $Cost_T$ = 11.6 €/MWh and average $Cost_I$ = 11.1 €/MWh).

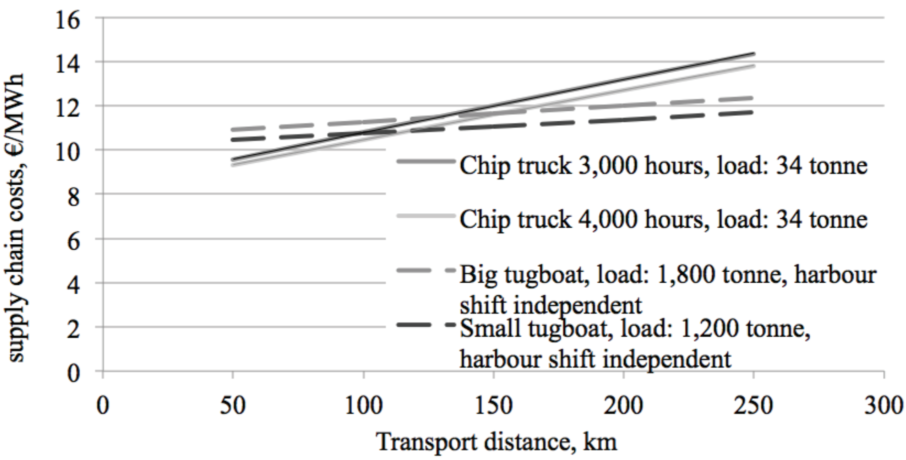

Figure 26. Cost comparison between road and waterway supply chain options (**Paper I**).

Paper II:
Large-scale container supply chains were the most cost-efficient alternatives and costs varied between 15.3 €/MWh and 16.9 €/MWh, whereas traditional supply chain costs varied between 16.1–18.2 €/MWh, the precise amount depending on the scenario used (540–740 GWh) (Figure 27). The total costs of the traditional supply chain were 5–10% greater than the corresponding container supply chain, depending on the scenario. Combined multimodal truck and railway transportation (Sce. 3) can be used to decrease unit costs for longer distances for traditional scenarios. The average of the scale 540–740 GWh was used for cost-efficient comparison and the result of supply chain cost-efficiency innovation averaged 7.1% (average $Cost_T$ = 17.4 €/MWh and average $Cost_I$ = 16.2 €/MWh).

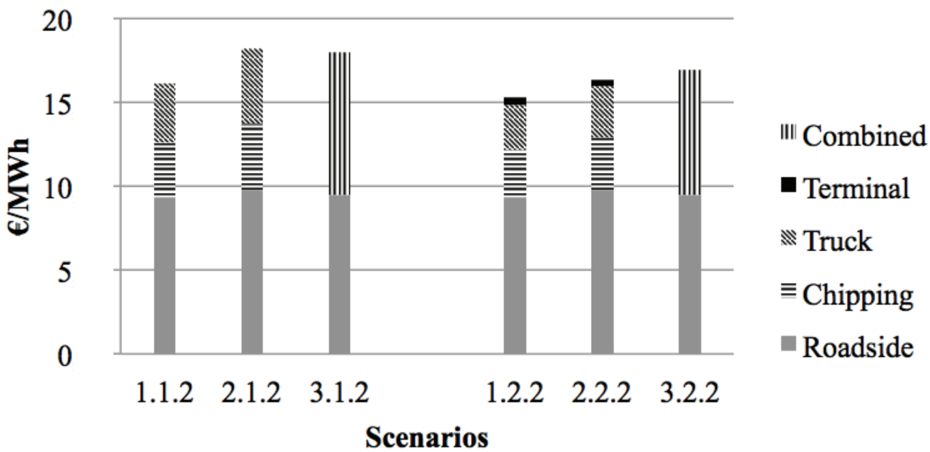

Figure 27. Unit cost (€/MWh) of traditional (1.1.2, 2.1.2, 3.1.2) and container (1.2.2, 2.2.2, 3.2.2) supply chain scenarios for truck transportation (Scenario 1, 540 GWh & Scenario 2, 740 GWh) and multimodal transportation (Scenario 3, 740 GWh) for forest chips. Combined = combined truck and railway supply chain.

Paper III:
The NIPFs were asked about the conditions in which they were willing to deliver different types of energy wood. Only on average one-fifth of forest owners did not want to sell small-diameter energy wood or logging residues for chipping. Instead, 43% of NIPFs were unwilling to sell stumps at all. According to these results, NIPFs would be most willing to deliver undelimbed whole trees, delimbed energy wood and logging residues.

Energy wood thinning was mainly perceived positively, with 65% of NIPFs reporting a willingness to carry it out. Forest owners with more than 100 ha of forest land were typically more willing to employ this method of forestry than those with small estates ($p< 0.037$). Generally, the main issues found to have significance in the NIPFs' perceptions of energy wood thinning were related to its use as a local energy source.

On average only one-fifth of forest owners did not want to sell small-diameter energy wood or logging residues for chipping. Percentage estimates of the willingness to deliver energy wood gained from the results were used in the forest biomass availability analysis (**Paper II**): small-diameter trees 80% (undelimbed whole tree 81%, delimbed energy wood

76%), logging residues 75% (exact 76%) and stumps 50% (exact 51%).

Energy wood thinning, a new forestry method, was mainly perceived positively, with 65% of NIPFs reporting a willingness to carry it out. Forest owners with more than 100 ha of forest land were typically more willing to employ this method of forestry than those with small estates ($p < 0.037$). Generally, the main issues found to have significance in the NIPFs' perceptions of energy wood thinning were related to its use as a local energy source, i.e. its potential to replace fossil fuels and thus restrict climate change.

Paper IV:

The roundwood removals of the first thinning were the starting point of the study. These were presented in relation to stand density before the first thinning. The average results cover all of Finland divided into Southern, Central and Northern regions. The first thinning removals (Figure 28) present how much roundwood (> 4 cm) can be harvested from the first thinning according to silvicultural recommendations. Average tree size (Figure 29) presents how large trees are taken away from these harvested stands.

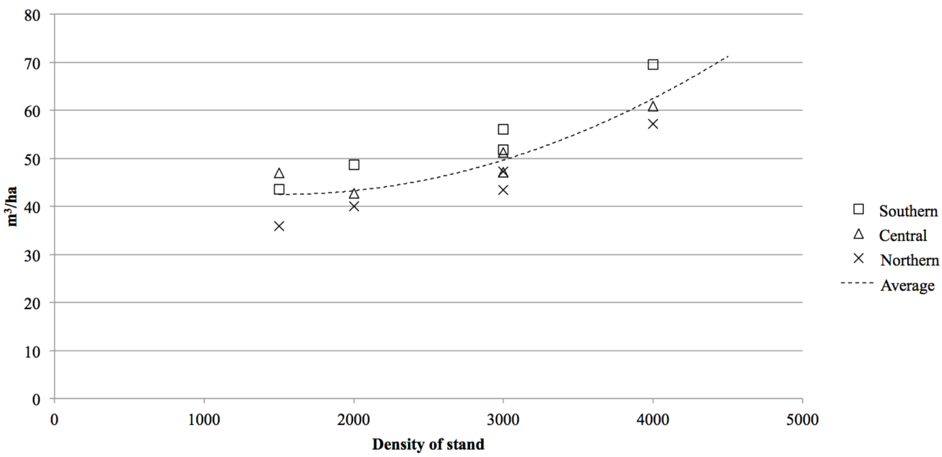

Figure 28. Removal for first thinning (trunk over 4 cm diameter) in relation to stand density before first thinning in alternative areas of Finland (Scenario 1.2), solid-m³/ha (**Paper IV**).

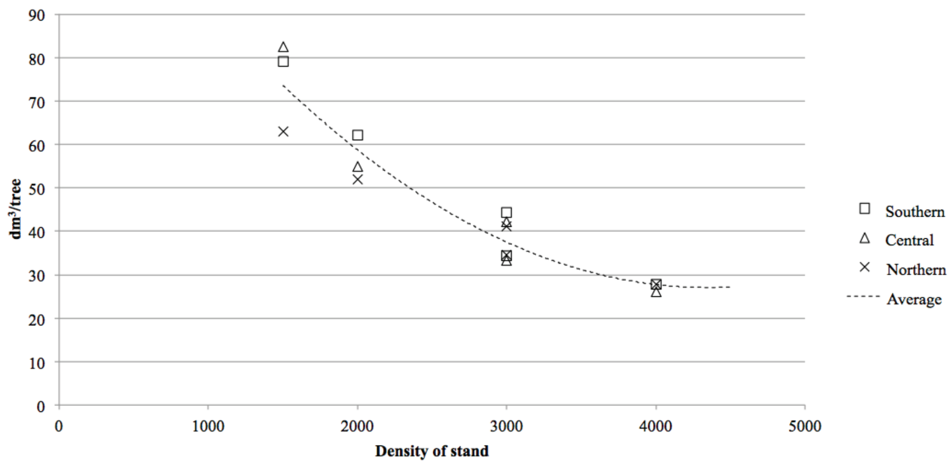

Figure 29. Tree size for first thinning (trunk over 4 cm in diameter) in relation to stand density before first thinning in alternative areas of Finland (Scenario 1.2) dm³/tree (**Paper IV**).

Total supply chain cost averages varied between 38.1 €/m³ and 44.3 €/m³ depending on the scenario and forest management regimes in place. The added value potential varied between -1.5 €/m³ and 4.7 €/m³ in relation to the baseline (forest management 4), which corresponds to relative variation between -3.5% and 10.9%. Stumpage prices of the first thinning removals were one of the main cost factors (22%–43%) of the overall supply chains in addition to logging costs (21–39%) (Figure 30).

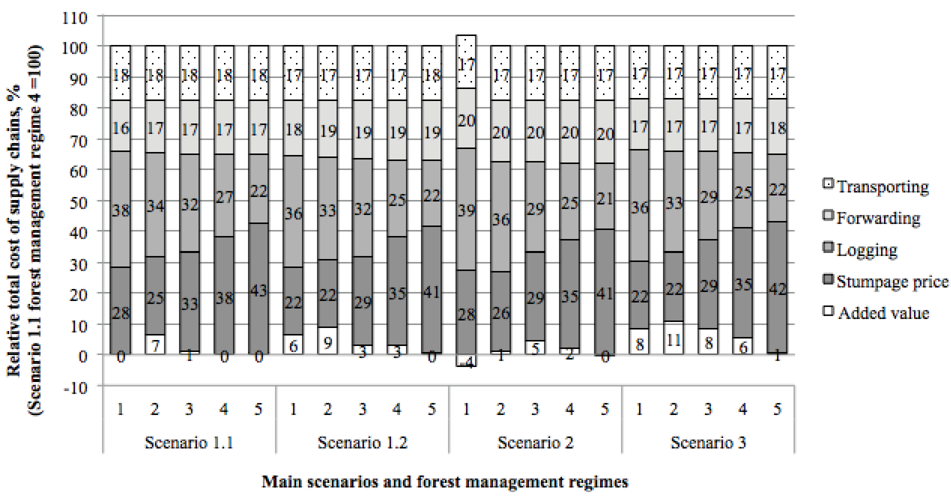

Figure 30. Relative total cost of small diameter supply chains (%) (**Paper IV**), where baseline cost is the scenario 1.1 (roundwood removals, > 6 cm) for a stand density of 2000 trees/ha.

The lowest costs were achieved for the 3rd scenario (delimbed energy wood removals > 4 cm) as an average cost for a density of 3000 trees per hectare and this was also the lowest density for all other scenarios. The supply chain costs for energy purposes (3rd scenario) is presented more closely for alternative fresh heath (MT) and dryish heath (VT) site types (Figure 31). The highest added value averaged 12.5% (5.4 €/m^3), and was gained for denser forest management (3000 trees per hectare) of the entire supply chain from dryish heath stands (VT) compared to the baseline (2000 trees per hectare, scenario 1.1, dryish heath stands) (average $Cost_T$ = 43.1 €/m^3 and average $Cost_I$ = 37.7 €/m^3).

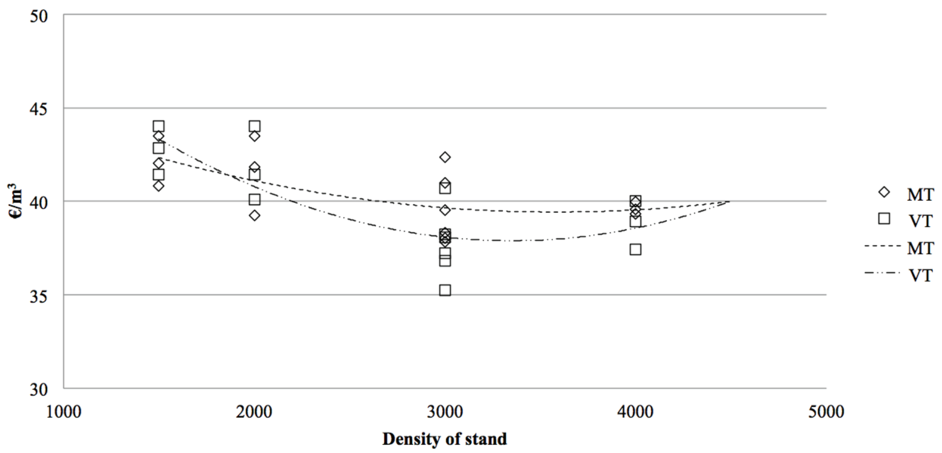

Figure 31. Total costs of small-diameter wood supply chain in 3rd scenario for energy purposes among fresh heath (MT) and dryish heath (VT) site type stands in relation to stand density (trees/ha) (**Paper IV**).

4.2. Adding value with innovation types

Results are presented as a cost reduction (=added value) comparison for the most potential options of the studied scenarios (Table 8) based on the results presented in chapter 4.1. Figure 32 presents the average cost comparison as percentage values with variance between minimum and maximum values for the main innovation types. It can be noted that the average cost reduction potential of incremental innovation was the lowest (4.3%) but it had the widest variance. Radical innovation presented the middle level in terms of cost reduction potential (7.1%) and variance. Network innovation represented the highest cost reduction potential (12.5%) but lowest variance between minimum and maximum values. This is because network innovation includes several structural holes with close connections between processes and systems that offer the possibility of finding more cost reduction potential for the entire supply chain.

Table 8. Cost reduction potential of innovation compared to traditional ones.

	Incremental innovation
Paper	Paper I
Forest biomass assortment	Logging residues
Traditional, supply chain	Truck supply chain (50 - 250 km)
Traditional, cost average of supply chain, [min-max] €/unit	11.6 €/MWh (*23.2 €/m^3) [9.3 - 13.8 €/MWh (~*18.6 - 27.6 €/m^3)]
Innovation, supply chain	Truck and barge supply chain (50 - 250 km)
Innovation, cost average of supply chain, [min-max] €/unit	11.1 €/MWh (*22.2 €/m^3) [10.4 - 11.7 €/MWh (~*20.8 - 23.4 €/m^3)]
Cost reduction, % (min-max)	**4.3 % (-12 - 15 %)**

	Radical innovation
Paper	Paper II
Forest biomass assortment	Logging residues and whole trees
Traditional, supply chain	Solid-frame truck and multimodal railway supply chain (540 - 740 GWh)
Traditional, cost average of supply chain, [min-max] €/unit	17.4 €/MWh (*34.8 €/m^3) [16.1 - 18.2 €/MWh (~*32.2 - 36.4 €/m^3)]
Innovation, supply chain	Container truck and intermodal railway supply chains (540 - 740 GWh)
Innovation, cost average of supply chain, [min-max] €/unit	16.2 €/MWh (*32.4 €/m^3) [15.3 - 16.9 €/MWh (~*30.6 - 33.8 €/m^3)]
Cost reduction, % (min-max)	**7.1 % (5 - 10 %)**

	Network innovation
Paper	Paper IV
Forest biomass assortment	Small-diameter trees (industrial roundwood or delimbed energy wood)
Traditional, supply chain	Density of stand, 2000 trees/ha (VT stands, 1.1 Scenario)
Traditional, cost average of supply chain, [min-max] €/unit	43.1 €/m^3 (**23.9 €/MWh) [42.0 - 44.8 €/m^3 (~**23.3 - 24.9 €/MWh)]
Innovation, supply chain	Density of stand, 3000 trees/ha (VT stands, 3 Scenario)
Innovation, cost average of supply chain, [min-max] €/unit	37.7 €/m^3 (***18.9 €/MWh) [37.0 - 38.2 €/m^3 (~***18.5 - 19.1 €/MWh)]
Cost reduction, % (min-max)	**12.5 % (10 - 15 %)**

*Change rate: 1 MWh = 0.5 m^3
**Change rate (moisture 55%): 1 m^3 = 1.8 MWh
***Change rate (moisture 35%): 1 m^3 = 2 MWh
/*Chipping cost is not included

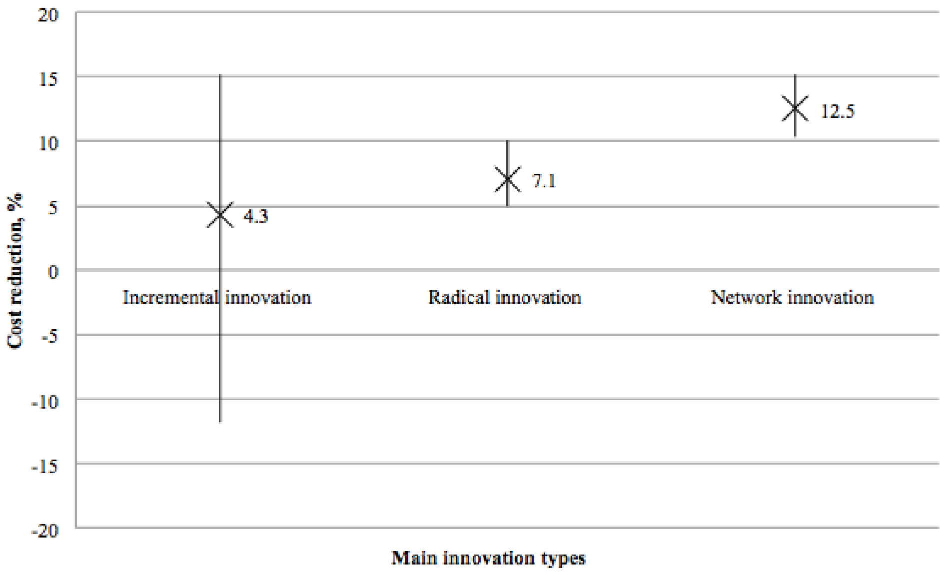

Figure 32. Cost reduction (%) associated with the main innovation types as average values (crosses) and minimum and maximum values (vertical segments).

5 DISCUSSION

5.1 Innovation strategy

Innovation is the most important part of a company´s strategy (Schumpeter 1934; Rumelt 1984; Porter 1985) and extends its network´s common business strategy for creating competitive advantage. Four innovation types can be categorised as either product, process, marketing or organisational innovation (Oslo Manual 2005), of which technological product innovations and innovativeness have played a major role in empirical studies (Garcia and Calantone 2001). In this work innovation strategy was applied to the process innovation of forest biomass supply chains, but there were close relationships in organisational and product innovations. The aim of innovation is to break the monopoly system (Schumpeter 1934), which could be kept as the traditional dominant technology or process. The traditional process is displaced with more innovative cost-effective alternatives to create more added value. It is significant to use the most suitable type of innovation strategy to gain the highest added value possible.

In the beginning, there is a need to identify which processes should be re-engineered, and which should be managed on the basis of continuous improvement (Davenport 1993). The business process re-engineering strategy must be seen as a cross-functional activity that needs to be integrated with other management aspects to be able to deliver benefits for the organisation (O'Neill and Sohal 1999). Continuous improvement strategies reflect on the incremental innovation type, whereas a business process re-engineering strategy resembles the origin of radical innovation type. A large number of terms are used in the definition of innovation types (Garcia and Calantone 2002), but the novelty is at least one of the unifying factors (Oslo Manual 2005). The novelty value of innovation can be divided into either new to the company, new to the market or new to the world (Oslo Manual 2005). One of the often-occurring shortages in both incremental and radical innovation types is the understanding of a company´s and its network´s needs for implementing the innovation process. The role of co-operative networks in innovation has been underlined in recent innovation studies. Network innovation was presented to define a value network business strategy to co-operate with the entire supply chain process.

Carr and Johansson (1995) identified two types of risk in the implementation of business process re-engineering: technical risk, which is a fear that the process changes will not work, and organisational risk, by far the greatest risk, which is the possibility of corporate culture reaction against the changes. A network risk can also exist, where the business environment around the company does not adapt to the change brought by innovation or is not ready for it at the time. Co-operative networking can be seen as one of the main innovation process studies and themes nowadays, and far more detailed research needs to be conducted as case studies (Pittaway et al. 2004). Empirical studies could similarly help analyse the functionality of alternative strategies in the cases of forest biomass supply chains. One of the challenges would be the categorisation of the innovation process types in the research of forest biomass supply chain operations.

The forest biomass supply chain has been studied from the operational point of view in recent years (Laitila 2008; Laitila and Väätäinen 2013), but only a few separate studies have focused on the forest biomass supply chain, using either strategy management of business process re-engineering (Windisch et al. 2013b) or the feasibility study approach (Jylhä, 2004; Ahtikoski et al. 2008) as the case of the network supply chain. Windisch et al. (2013b) theoretically studied business logistics in forest biomass procurement operations by using business process re-engineering methodology on a system level, which showed a 20–39% cost-saving potential by redesigning biomass procurement. A simulation method could facilitate business process re-engineering in a more scientific way (Su et al. 2010). Simulation could be useful regarding know-how and technology transfer in the field of biomass for energy procurement, and provide the importance of process management by simple and low-cost simulation measures used for the improvement of forest supply systems (Windisch et al. 2013b). On the one hand, simulation as a theoretical study method can be fast and cheap, but on the other, its relevance for practical decision-making and innovation implementation may suffer. The main idea for using a variety of methods in this work was to combine practical study methods with simulation as theoretical research. More realistic study results can be achieved by using a variety of methods to evaluate the possibilities for practical innovation use.

According to Röser (2012) a simple technology transfer in the supply chain system is not enough to be successful in the market. Combining technology and know-how to be transferred with existing expertise creating innovative knowledge and solutions is also needed (Röser 2012). In some cases it is possible to create success process innovations by implementing small changes to current systems, but there must be a strong need for systems in practice. For example, waterway transportation of forest chips has been used when the need for forest chips has been strong. Innovation strategy must decide whether to develop inland barge transportation at incremental steps in process transfer (roundwood barge transportation to chip transportation), organisational change (a co-operative waterway system as control centre) or even more radical innovation aiming e.g. to make inland vessel transport possible in winter. An incremental innovation strategy is not always enough to maintain competitiveness. On the other hand, waterway transportation could be innovated as part of the overall supply chains.

Continuous improvement as a business strategy utilised a type of incremental innovation (**Paper I**). Business process re-engineering as a business strategy instead utilised a type of radical innovation (**Paper II**). Value network as a business strategy was additionally studied as a case of an overall supply chain system of the network innovation type (**Paper IV**). Network innovation can be seen as an applied follow-up concept between the value chain theory of an individual company (Porter 1985) with the network of other stakeholders and industry sector based on the cluster theory (Porter 1990; Porter 1998). Network innovation concentrated here more on innovation strategy applied in the forest biomass supply chain. Innovation creativity is based on the ability to utilise the innovation strategy of organised knowledge flows. Traditionally, co-operation of knowledge flows of alternative companies´ co-operation have been seen as vertical innovation, where either top-down or bottom-up flows can happen. Network innovation means either a horizontal knowledge flow between an individual company´s activities or enlarged knowledge flows between a company and its whole network in the same sector. The idea of a value chain of forest biomass supply chains is already taken into account as part of both continuous improvement strategies (incremental innovation) and business process re-engineering (radical innovation) to define the cost reduction potential as added value. The difference between the value chain as part of strategy (continuous improvement, business process re-engineering) and value chain as network innovation is that the value chain strategy connects one business system (logistics process) with several activities (**Paper I, II**) to co-operate as vertical innovation with other business systems of supply chains, whereas the value chain as network innovation connects two or more separate business systems together (**Paper IV**) to form the whole process supply chain innovation. The strategy management of a value network could be utilised for developing the cost-efficiency of the forest biomass supply chain and utilised for network innovation in knowledge flows.

In this work network innovation was regarded as a process type and organisational innovation that has a larger impact on the extended forest biomass supply chain processes with the co-operativeness of the entire network. However, the innovation types, and network innovation in particular, need more case studies to prove their effectiveness in innovation. The comparability of study cases additionally needs closer attention. In this work, comparability of innovation types was presented as the cost reduction (=added value) potential in the form of percentages, which were results between the traditional case as baseline and innovative cases as references. The innovation type study cases exhibited a great amount of variances between each other. The chosen scale is an important aspect of the comparisons, and the chosen scenarios are another. The chosen scale was the result of the main case study scenarios. In this work, the innovative cases of the most promising innovation case scenarios were chosen as the reference scenario. The innovation scenario was compared either to the traditional option of the same scenario or to the traditional baseline scenario of the entire study.

5.2 Implementation of innovation in the case studies

Incremental innovation (Paper I)

This case study presented a type of incremental innovation with the aim of improving the operational efficiency of the barge transportation supply chain for forest chips. The innovation purpose was to operationally develop cost reduction for long-distance logistics. The business strategy was based on continuous improvement with the aim of changing traditional strategies in two ways. Firstly, in addition to the traditional truck transportation concept for forest chips, waterway transportation was taken into use as a long-distance transportation mode. This represents a small change in business strategy by including one supporting activity for company procurement. Secondly, traditional barge transportation used for roundwood was changed slightly for it to be utilisable in the supply chain of forest chips.

Combined practical demonstrations with discrete-event simulation proved the possibilities and cost-efficiency potential of the barge transportation supply chain. The demonstration revealed new information of the energy density of forest chips, which were an average 25% more dense in large-scale barges than in the truckloads. Improving energy density is one of the most crucial aspects of cost-efficient forest biomass transportation. Demonstrations additionally provided ample amounts of productivity information and experience on alternative supply systems concerning truck transportation, chipping operations, loadings and barge transportation. However, the discrete-event simulation model was needed to take into account all the important logistics interactions and their impacts in the waterway supply of forest chips. A variety of methods provided important findings for innovating supply chains by waterways for long distances.

Forest fuels, especially forest chips, can be transported along inland waterways by barges. If the harbour and barge logistics are managed well and barge structures are fit to match the efficient forest chip transportation, the waterway supply chain may be cost-competitive at transport distances surpassing 100–150 km with the conventional supply chain along roads by chip trucks. The longer the distance, the better the relative cost-efficiency of the waterway supply chain. A winter season (3–4 months) with ice-covered lake areas decreases the efficiency of waterway systems.

A co-operative waterway system was presented as a model to organising the waterway supply chain as an efficient method for all wood users. Independent entrepreneurs could operate as barge operators but all transportations could be organised via a co-operative waterway system functioning as a control centre to supply materials to the demand sites. The lowest and highest transport performances of one transport unit were 174 GWh and 774 GWh per annum, whereas the total consumption of biomass was 2620 GWh with all three case power plants combined. An inland waterway supply chain including satellite terminals next to the waterways may be cost-competitive for the power plants that are close or next to waterways and that require larger amounts of forest chips than truck transports could cost-efficiently supply.

Incremental innovation methods were divided into the innovation type (process) and sub-type (organisational). In main process innovation, the traditional barge transportation was changed operationally to allow for the loading and unloading of forest chips instead of roundwood. This was connected to the current process of forest biomass truck transportation, which was used in the hauling operations from the forest roadside to the harbour terminal. The modification made in the harbour terminals was replacing the roundwood buckets in the loading and unloading machines with chip buckets. Wheeled loaders were additionally needed in terminal operations and a belt conveyor for wood chips was also tested in the company´s own demonstration. The innovation strategy type can remain as closed innovation for process innovation developing the operational barge transportation supply chain, because company-specific methods are usually developed during actual work conditions, except in this study where they were based on the project where several transportations were organised in public.

The sub-type of organisational innovation meant the co-operative waterway system as the common control centre for barge transportation. Organisational innovation was the starting point for the theoretical barge transportation simulations and process innovation. This could allow the cost-efficient transportation of forest chips to several end-use facilities. The organisational change would require large actions from the current organisations and maintain elements for radical innovation. The innovation strategy type can be kept as open innovation for the organisational innovation of co-operative waterway system.

Incremental innovation can after all be kept at a moderate risk level because developing does not require much new equipment for applying logistics operations into practice. Incremental innovations are the most common type of innovation, because they are fast to implement. Incremental innovation is an example of top-down innovation, where managers in charge of supply chain operations can decide the level of change. Innovation knowledge flow began as changing of the organisational system in the traditional roadside chipping chain for energy wood and traditional barge transportation chain for roundwood. The methods can be applied if the demand for forest fuels is growing and forest biomass is needed from long distances. The prerequisites for the waterway supply chain of forest chips are existing equipment, routes and harbour terminal facilities along with good forest fuel resources and a large-scale plant.

Radical innovation (Paper II, III)

Radical innovation is needed when incremental innovation is not enough to maintain competitive advantage. Study (**Paper II**) presented radical innovation, in which the aim was to improve the cost-efficiency of the intermodal container supply chain for forest chips. The innovation purpose was to research the cost reduction potential of large-scale logistics. Business strategy was based on business process re-engineering aiming to completely change the traditional strategies of transporting forest chips with solid-frame vehicles. This presents the business strategy by changing the entire logistics process from forest roadside storages to the plant.

The intermodal container concept can be regarded as a radical product that also changes the entire supply chain process. This study was an example of a forest biomass supply chain strategy as business process re-engineering. A variety of methods were used in the simulation to gain practical relevance in the theoretical studies. The study included a GIS model combined with a simulation model to calculate the costs of a number of scenarios for the case area of Central Finland. The simulation study was carried out using an agent-based simulation method to enable the calculations incorporating several truck options, including variable factors connected to GIS-based availability analysis. The variety of methods provided greater relevance to practical decision-making when considering the use of radical innovation of a lightweight composite intermodal container concept. Simulation as a study method is useful for updating the model when road dimensions were changed as political decisions. Lättilä (2012a) encouraged the use of simulation more in practical business decision-making with a separate user interface. The simulation methods can be used to estimate the opportunities for process innovations before placing them into practical use. As simulation allows for the randomness and interdependence of variables in the system (Asikainen 1995), it may enable a more realistic description of the system.

The variety of methods used as the study method needed a lot of special knowledge of biomass procurement processes, simulation and GIS techniques, and information data to enable a workable model for exact decision-making. The forest biomass availability study included novel GIS techniques in a competitive situation for forest fuels (Korpinen et al. 2012) with forest owners´ willingness to deliver energy wood (**Paper III**). The results, using the combined biomass availability analysis and simulation study method, showed that the most advantageous way to expand the procurement area for forest chips is either to use composite container trucks around the end-use facility or start using multimodal truck and train transportation from longer distances. The main prerequisite for the use of the container concept is based on the sufficient amount of biomass delivered via the system. On the other hand, a comparison of case studies presented the theoretical description for completely renewing the supply chain system. Combined methods incorporating not only truck and railway supply chains but also traditional and container supply chains might achieve optimal solutions for the large-scale supply chain of forest biomass.

One reason for cost-efficiency was the light structure of the composite container, which can allow for more payload and efficient handling operations. The improved payload capacity can be achieved in truck transportation by using light structure containers. A light structure provides payload advantages when the maximum truck weight is limited and biomass is heavy enough, though the weight dimension has been increased in Finland and thoroughly dried forest chips are a light material. The other benefits of composite containers include intermodal usability and integration possibilities to the current systems (Ranta et al. 2011), RFID-technology without metal disturbance (Föhr et al. 2014; Ranta et al. 2014b) as well as non-freezing of the biomass (Föhr et al. 2013). Only one of these advantages could have allowed the level of radical product innovation.

The risk of radical innovation of the container concept is that the most important network must also be adapted to the new process, unless the changes can be implemented in their own sub-systems. If the network is not able to adapt to the changes, it is not possible to get full benefit out of the radical innovation and business advantages may be missed. Radical innovation could be kept as a high risk operation. The entire value network should take the innovation processes into consideration.

Business process re-engineering as a business strategy utilises radical innovations to change the traditional supply chains. These radical innovation methods were divided into an innovation type and a sub-type. The innovation type was the process innovation of an intermodal container system. The traditional solid-frame truck transportation and railway transportation processes were changed radically to be able to handle containers as units instead of loose forest chips. The bulk material handling of forest chips was replaced with intermodal container units. The innovation type can be kept as open innovation for researching radical container supply chain solutions as a form of co-operation with companies and researchers in public projects. The innovation sub-type was product innovation, which was based on developing light-structured intermodal composite containers as the product. The product innovation was the main starting point for the theoretical simulation of supply chains. The innovation product type could be kept as closed innovation because it was developed and owned by an individual company including patents. Radical innovation was an example of bottom-up innovation, where innovation knowledge flow began with an individual product and ended up changing the entire supply chain system of forest chips.

Paper III included the corrections of forest owner´s willingness to deliver energy wood used in the biomass availability analysis. The study proved that alternative energy wood assortments have different delivery potentials for energy purposes. Small-diameter trees and logging residues are favoured by forest owners while stumps are not. The site-dependent availability analysis supplemented with the survey results of forest owner´s willingness to deliver energy wood showed that it is possible to decrease truck-driving distances dramatically if the additional procurement is extended via a railway satellite terminal with good biomass reserves rather than through direct truck hauling at the area of high demand and competition. On the other hand, additional handling and railway operations increased the total supply chain costs for the intermodal container supply chain more than direct truck hauling.

The study shows that both the production of small-diameter energy wood and employment of energy wood thinning as a method of forestry are positively perceived by the NIPFs. This appears to offer a great potential for the regional energy sector for increasing its energy wood supply in the future. However, this potential needs to be activated among the NIPFs, while not forgetting logging technology development and stumpage price levels for energy wood. According to this study, activating the energy wood supply among NIPFs requires the development of market practices e.g. market prices for different types of energy wood and measurement ways. Willingness to sell roundwood has been determined by econometric studies on the relationship between the roundwood supply and the price to estimate supply price elasticity in Finland (Toppinen and Kuuluvainen 1997). The method could be used for energy wood when reliable price data are available for a long period.

Network innovation (Paper IV)

The aim of network innovation was to improve the added value (cost reduction) of the entire supply chain for small-diameter trees. The purpose of innovation was to innovate the whole added value (=cost reduction) of the supply chain. Business strategy was based on value networking aiming to reorganise forest biomass supply chains. This presents the business strategy by covering the entire process of forest biomass supply chain networks starting from the forest owner´s decision-making and continuing with the options of harvesting and logistics and ending up at the plant to fulfill customer needs to add value by reducing costs of the overall process.

An added-value innovation system was studied as a process innovation type for producing and delivering small-diameter trees from the first thinning. The sub-type can be kept as organisational innovation, because the process includes several separate business systems, which need organisational co-operation as an entire network. The traditional baseline process presented a separate roundwood supply chain for industrial use, whereas innovative processes tried to seek the optimal cost-efficiency for either separately or integrately produced and supplied industrial wood and/or delimbed energy wood as a whole process. This was implemented by increasing the minimum top diameter of delimbed energy wood in the cutting operation and decreasing the minimum top diameter of pulp wood. The innovation strategy type could be kept as open innovation, because the aim of the system was to achieve advantages for every separate part of the whole system as a combination. On the other hand, the innovation strategy type was categorised to be implemented as outside of company because it was based on research know-how.

Forest stand simulation brought useful information to improve the whole supply chain costs of small-diameter trees. Stand density before the first thinning had an opposite effect on tree removal and size in the thinning. Tree removal and size influenced the harvesting costs. Optimal stand density is important when determining optimal harvesting and further the entire supply chain. According to this study it was more cost-efficient to consider growing stands densely at 3000 trees per hectare and aiming at either separate harvesting and the use of industrial roundwood (Scenario 1.1) or separate harvesting and the use of delimbed energy wood (Scenario 3). Integrated harvesting methods (Scenario 1.2 and Scenario 2) for collecting both industrial roundwood and delimbed energy wood were also more cost-efficient for denser forest stands at 3000 trees per hectare. After all, the denser forest management (3000 trees per hectare) was the most cost-efficient, aiming at separate harvesting and a supply chain for delimbed energy wood (Scenario 3), when the entire value chain was taken into account as forest management and logistics to the plant. A forest stand simulator (MOTTI) has been developed and used in several studies (Hynynen et al. 2005; Ahtikoski et al. 2008;

Heikkilä et al. 2009). Research using this information in the further analysis of the total supply chains of forest biomass is missing despite the high quality equipment available for stand simulation. Study methods could bring opportunities for exact site-dependent value descriptions of alternative forest management producing different timber assortments to the local markets.

Network innovation succeeded as a method in combining two separate business process systems (forest owners and logistics) to improve the overall added value of the forest biomass supply chain. The idea was tested by combining forest management simulations with logistics cost analysis to improve the cost reduction as the added value of small-diameter trees. The study showed that stand density must be well designed and organised in practice to achieve added value from the first thinning. The cost of small-diameter wood supply chains is sensitive to the optimal level of stand density and other variable factors such as site type and region or forest biomass moisture content. This study pointed out that not only does the profitability of forest management matter but so also do the supply chain costs. This means that forest resource system economics must be studied in their totality and site-dependently related to the use of biomass. It also means that the innovation development of forest resource and supply chain management must be studied in their totality.

Though denser forest management has been included in the silvicultural recommendations (Hyvän metsänhoidon… 2006; Äijälä et al. 2014) as an opportunity, the method is marginally used in practice as a systematic forest management technique. Denser forest stands grow more biomass at the beginning of the forest rotation, but the average stem size of the trees remain smaller during the first thinning compared to traditional forest management. Though the integrated harvesting of young stands is a fascinating opportunity for concurrently considering both logwood, pulpwood and energy wood, the whole supply chain for energy purposes from denser stands was found to be the optimal choice according to this study. The scenarios for the separate harvesting of industrial wood or the integrated harvesting of industrial and energy wood were more expensive. Case study suggests that in some places it is worth considering the denser forest management regime supplied for energy purposes.

Especially the use of small-diameter energy wood could be increased to reach energy targets within the Finnish national context. Denser forest management of young stands, including energy wood thinning, can be used to produce small-diameter trees more economically (Heikkilä et al. 2009). On the other hand, logging is the most expensive part of the supply chain for small-diameter energy wood (Laitila 2008), and the costs are significantly higher than for logging residues (Hakkila 2004). Innovations leading to more efficient logging have been developed in recent years, such as single-grip harvester heads equipped with multi-tree handling equipment for cutting whole trees and multi-stem delimbed energy wood (Laitila et al. 2010; Belbo 2011; Kärhä 2011). Other costs of the supply chain, such as chipping and chip transportation, are quite similar for both small-diameter trees and logging residues (Hakkila 2004; Laitila 2008). The cost results of the delimbed energy wood supply chain without subsidies presented in this case study seems to be reasonable compared to earlier studies of small-diameter trees supply chains. According to earlier studies, the costs have varied between 32 €/m^3 and 42 €/m^3 (Laitila 2008) in the study of whole-tree supply chains and between 33 €/m^3 and 50 €/m^3 (Petty 2014) in the study of delimbed stemwood supply chains. The supply chain costs of delimbed energy wood additionally seems to be lower than the average price paid for forest chips in 2013 (20.7 €/MWh, Statistics Finland 2014). However, the forest industry´s paying capability for energy wood may be lower than for pulpwood, and the harvesting of small-diameter trees for energy becomes a rational alternative if the price levels approach each other (Jylhä 2011). No significant technical barriers exist to using undelimbed whole Scots pine trees, either loose or bundled, in kraft pulp mills (Jylhä et al. 2010), which may enable choosing the most cost-efficient method from young thinnings between undelimbed whole trees either separated or integrated into bundles, or delimbed wood either separated or integrated, for the use of industrial and/or energy purposes.

However, the logistics system as part of the whole supply chain may contain several separate entrepreneurs´ business units in practice but in this context the logistics is kept as one system itself. Whereas previous innovation processes have been studied mainly by taking one system (such as logistics) into account (**Paper I, II**), **Paper IV** considers network innovation beginning from the forest owners´ decision-making of property, and continuing with logistics alternatives to finish with the plant as a buyer of forest biomass for either wood production or energy purposes.

Paper IV considered the plant as the final customer of the forest biomass supply chain, but the value network could be continued to the final customers to optimise plant decisions for refining biomass for alternative uses providing value to the final consumer. Network innovation can be seen as an expansion of normal company value chains with primary and supporting activities (Porter 1985) to the value chain network and to business systems as combined to overall supply chain innovation. The concept is close to the cluster theory (Porter 1998), of which we mention an example for the forest cluster in the case of a Portuguese sawmill that suffered from poor quality because landowners did not invest in timber management. As a result, the supply chain had to be developed as a whole unit and simultaneously with co-operation with landowners, logging operations, sawmills and marketing. Whereas Porter (1985) highlighted the importance of horizontal support activities to connect vertical primary activities together inside the company to create value, the same development could be applied for creating innovations. Though the structural holes between network actors have been seen to be significant in innovation (Burt 2004), horizontal connections should be able to support them. The role between vertical and horizontal knowledge inflows in organisation innovation should be paid attention to for contributing to the company´s competitive advantage (Mom et al. 2007) and alternatively applied to the entire network cooperation. Knowledge flows are an important source for success in network innovation.

The method may have significance for developing the innovation processes of a company or its network, which wants to optimally innovate it´s overall business activities, systems and network. Knowledge flows vertically and horizontally in innovation, and the whole supply chain network can participate in the added-value processes. This enables estimating the added-value potential of either the sub-systems or the overall supply chain, which enables a mild risk level by estimating and implementing innovations in practice. The main risk of the method is that changes in the supply chain must be started in correct forest stands from pre-commercial thinning operations years/decades before the cutting timing of the first thinning, whereas changes in market situations are faster. Innovation speed is also a risk, which might be slower in co-operation innovation than in incremental innovation as a company-specific model. On the other hand, the company with the strongest organised network or its own procurement system and forest property could dynamically innovate the entire supply chain. The methods presented in the case study can be taken into use if the demand of small-diameter trees is expected to grow in either the use of pulp or energy purposes in the middle to long term. Network innovation represented the highest average cost reduction potential in the case of a forest biomass supply chain for small-diameter trees, which can be kept as the most potential innovation type applied for forest biomass supply chains.

6 CONCLUSION

Innovation is a key factor for a company and its network strategy management to achieve competitive advantage. The aim of innovation is to replace traditional dominant technologies or processes in a new way, which enables more advantages to the company, its network or customer. Several innovation cases were determined in this work and were divided into incremental, radical and network innovation types. It was possible to achieve the advantage as a cost reduction by innovating traditional forest biomass supply chain processes in a novel way. However, the achieved cost reduction was not always self-evident. The cost reduction potential in process innovation was dependent on the innovation case and type. Incremental innovation was described as the case of a waterway supply chain for forest chips, which provided a cost reduction if the distance was long enough compared to the traditional truck supply chain. Radical innovation was studied as a case of an intermodal container supply chain for forest chips, which provided cost reduction depending on the scenario if the system quantity was large enough. Network innovation was presented as a new type of innovation applied to the forest biomass supply chains for small-diameter trees. The case of network innovation, presenting the co-operation of the entire supply chain by linking business systems of forest management and logistics together as process innovation provided the highest cost reduction as added value. According to the studies, co-operation in process innovation could be recommended in forest biomass supply chains.

However, the role of competition and co-operation should be paid attention to in the further general research of innovation types and in closer studies of the forest biomass supply chain cases. The origin of innovation deals on the one hand with breaking the monopolies in the market and on the other hand in creating the competitive advantage aiming at a leading position in the market. According to this work, a leading position by creating added value in the forest biomass supply chain could be achieved with co-operation in network innovation. The leading position by competitive advantage is important for a company and its network in the short-term, but may achieve an imperfect market situation in the long-term. An imperfect market situation may influence the inefficiency of the general market economy in the long-term. In innovation process it is important to create co-operation in processes, while upholding the competition situation in a local business. The chosen general innovation type should support both co-operation and competition at the regional level. It is important to note that the companies in co-operation processes do not need to give up their own innovativeness. Co-operative network innovation can be seen as an additional element for a company´s own innovation.

Due to the increase of forest biomass transportation in the future, more environmentally sustainable, energy efficient and cost-competitive transportation methods such as waterway and railway transports should be favoured in places where they are feasible. This study presented empirical results for several case studies of forest biomass supply chains. According to the study, the overall supply chains using optimal site-dependency of forest resources, chosen logistics and plant production should be paid more attention to. By innovating entire forest biomass supply chains it is possible to replace traditional dominant technology or process and gain more profit for the company and its network in the short-term or more added value for customer in the long-term. A competition market situation defines how the profit, e.g. added value gained by cost reduction, is divided between the supply chain network and the customer. This work presented the network innovation for estimating the entire added value for the forest biomass supply chain.

The main conclusion of this work is that it is not worth implementing innovation only on the inside of company´s own activities, but opening the innovation process for the entire supply chain network is crucial. The co-operative innovation process was seen as an important part of a company and its network strategy to add value. Unless network innovation is seen as the most potential innovation type, it would be important to estimate the situations and companies where the methods can be utilised. The methods presented in this work could be mainly applied in forest biomass supply chain innovation. Methods could additionally be applied in the whole forest and energy clusters developing regional or national innovation policy to aim at cost-effectively utilising overall forest property, logistics and plant production. In future studies, it would be important to enlarge forest resource supply chain approaches from the economical sustainability issues for improving the advantages of other aspects, such as ecological and social sustainability or the mitigation of climate change.

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