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Methodology for choice of harvesting system for energy wood from early thinning

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Academic dissertation

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ABSTRACT

The primary aim of the present study was to develop a methodology for estimating the procurement cost of forest chips from early thinnings. The most common logging systems and supply chains of forest chips used in early thinnings in Finland were compared at stand and regional level using productivity models and cost parameters obtained mainly from the sub-studies of this thesis. Furthermore, a decision tree was constructed for selecting harvesting method for energy wood originating from early thinnings.

Forwarding productivity following mechanised cutting was significantly higher compared to productivity after motor-manual cutting. Mechanised cutting by the harvester enables felling and bunching of whole trees into large grapple loads close to strip roads, which facilitates increasing forwarding output and reducing costs. The two-machine system comprised of a harvester and a forwarder was the most cost-efficient logging system due to higher efficiency in cutting and especially in the forwarding phase. The cost of motor-manual whole-tree cutting was equal to mechanised whole-tree cutting, while forwarding cost after motor-manual cutting was almost double that after mechanised cutting. Using a forwarder-based harwarder resulted in the highest logging costs. However, with large tree volumes and removals its costs were almost equal to those of motor-manual-based logging. In order to achieve a breakthrough for the harwarder system, costs must be reduced by improving both machine technology and working techniques.

Available volumes and procurement costs of fuel chips made of small-diameter trees were compared at regional level. The trees were harvested either by the multi-stem delimbed shortwood or whole-tree method and chipped by a truck-mounted drum chipper at the roadside. Based on the availability analysis, delimbing reduced regional cutting recovery by 42% compared to whole tree harvesting, when the minimum concentration of energy wood was set at 25 m^3 ha^{-1}. Delimbing reduced the recovery rate of biomass thereby also reducing the number of potential harvesting sites with adequate removal rates. However, the study showed that forest energy potential can be increased and procurement costs reduced by applying the shortwood method with multi-stem delimbing in stands stands where whole tree harvesting is not recommended because of potential nutrient losses or other ecological reasons. Using versatile machinery in thinnings increases the flexibility of forest operations and thereby improves cost-efficiency.

Keywords: harvesting, whole trees, multi-stem delimbed shortwood, forest chips, productivity models, procurement cost

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Finally, I want to express my deepest gratitude to my parents for their love and constant support.

LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. These papers are reprinted with the permission of the respective publishers.

I Laitila, J. & Asikainen, A. 2006. Energy wood logging from early thinnings by harwarder method. Baltic Forestry. 12(1): 94–102. http://www.balticforestry.mi.lt/bf/index.php?option=com_content&view=article&catid=25&id=191

II Laitila, J., Asikainen, A. & Nuutinen, Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. International Journal of Forest Engineering 18(2): 29–39. http://journals.hil.unb.ca/index.php/IJFE/article/view/5709/6714

III Laitila, J. 2008. Harvesting technology and the cost of fuel chips from early thinnings. Silva Fennica 42(2): 267–283. http://www.metla.fi/silvafennica/full/sf42/sf422267.pdf

IV Laitila, J., Heikkilä, J. & Anttila, P. 2010. Harvesting alternatives, accumulation and procurement cost of small-diameter thinning wood for fuel in Central-Finland. Silva Fennica 44(3): 465–480. http://www.metla.fi/silvafennica/full/sf44/sf443465.pdf

The author is fully responsible for article III and the text of this doctoral thesis. He was the main author for articles I, II and IV and had the main responsibility for all calculations, data analyses and writing. The co-authors of articles I, II and IV have improved the work by commenting on the manuscript and were involved in the collection of time study data.

CONTENTS

1 INTRODUCTION

1.1 Background

The number of heating and power plants using forest chips has increased from 250 units close to 1000 units during the last ten-year period in Finland (Asikainen and Anttila 2009). Furthermore, several new biomass plants are planned or under construction (Laitila et al. 2010b). In 2007 the Council of Europe accepted the proposal of the European Commission that the EU member countries should produce 20% of their energy using renewable sources by the year 2020. Each member country has its own target. The EU obligates Finland to increase the share of renewable energy sources in energy consumption from 28.5% to 38% by the year 2020 (Pitkän aikavälin ilmasto- … 2008).

The Finnish long-term climate and energy strategy assigns wood-based energy an important role in achieving this goal (Pitkän aikavälin ilmasto- … 2008). Currently, processing residues from the forest industry are the most important source of wood-based fuels, but these by-products can be considered to be fully utilised at the present time (Ylitalo 2010). In addition, the availability of processing residues has decreased during the last few years as a consequence of the closure of several pulp and paper mills and the decreased production of sawmills and plywood mills (Kallio 2009, Kallio et al. 2011, Ylitalo 2010). Thus, the most important means of increasing the consumption of wood for energy in the future is the utilisation of forest chip resources (Pitkän aikavälin ilmasto- … 2008).

In Finland the potential sources of raw material harvested from forests for energy use include felled trees (whole trees, including crown or stems without branches) and components of trees that do not fulfil the requirements for industrial use (Kärkkäinen et al. 2008). Felled trees are rejected for industrial use due to reasons such as small size (e.g. trees removed for silvicultural reasons in pre-commercial thinning of young stands) or poor quality. The tree components rejected for industrial use include tops of stems, living and dead branches, foliage, off-cuts of stems, stumps and roots (Kärkkäinen et al. 2008, Hakkila 2004).

The Ministerial Working Group of the Finnish Government for climate and energy policy has set the target that 13.5 million solid cubic metres of forest chips – i.e. logging residues and stumps from final fellings and small trees from early thinning – will be used for energy in 2020 (Työ- ja elinkeinoministeriö 2010). In addition, a significant amount of forest chips is planned to be used as a feedstock for transportation fuels, as the annual production target for transportation fuels in 2020 has been set at 7 TWh (Työ- ja elinkeinoministeriö 2010). In order to reach these ambitious targets set for forest chip use by 2020, the production costs of fuel chips must be decreased and the quality and the security of fuel supply must be improved (Laitila et al. 2010b). This can be achieved by means such as developing the production technology, business models and logistics of forest chips. It also calls for great investments in production machinery and the end-use facilities as well as a large skilled workforce (Kärhä et al. 2010, Laitila et al. 2010b).

1.2 The current use and harvesting potential of forest chips

1.2.1 The current use of forest chips

In the year 2010, Finnish heating and power plants consumed 16.0 million m^3 (solid) of wood fuels, of which 6.2 million m^3 comprised forest chips (Ylitalo 2011). About 41% of these forest chips were made of small diameter thinning wood produced in the tending of young stands and 36% was produced from logging residues in final felling. The share of the stump and root wood was 16%, while 6% of forest chips were produced from large and rotten roundwood (Ylitalo 2011). In addition, about 0.67 million m³ of forest chips are used annually to heat small-sized dwellings, i.e. farms and both detached and terraced houses (Ylitalo 2011). The use of forest chips in Finland has increased very rapidly since the beginning of the 21st century. In 2000, the total use of forest chips was only 0.9 million m³ (Ylitalo 2011).

1.2.2 The estimation of forest chip resources

Several estimates have been made during the last ten years to determine the potential recovery of raw material for energy wood in Finland for different purposes by using the existing biomass equations and coefficients (e.g. Malinen et al. 2001, Ranta 2002, Hakkila 2004, Ranta 2005, Ranta et al. 2007, Maidell et al. 2008, Kärkkäinen et al. 2008, Laitila et al. 2008, Asikainen et al. 2008, Kärhä et al. 2010, Mantau et al. 2010, Verkerk et al. 2011). In general, the estimates have been based on the national forest inventory data (e.g. Hakkila 1992, Laitila et al. 2004, Heikkilä et al. 2005) but the quantities have also been estimated on the basis of forest companies' stand data (Asikainen et al. 2001, Ranta 2002) and official cutting statistics (Hynynen 2001, Asikainen et al. 2008). The available volumes have also been evaluated in light of regional combinations of forest plans and the treatment plans of the State Forest Service and the forest companies (Leiviskä et al. 1993). MELA software has been developed for the examination of alternative treatment options and cutting scenarios of the forests and Energia-MELA for energy wood calculations (Mielikäinen et al. 1995, Malinen and Pesonen 1996, Keskimölö and Malinen 1997). It is also possible to use forest-planning data for estimating the available volumes of energy wood (Pasanen et al. 1997).

The amount of residues left in the forest after cutting is mainly dependent on tree species, size and branchiness of felled trees, and the amount of decayed wood (Kärkkäinen et al. 2008). The production potential is also dependent on how much forest and what kind of forests are cut, e.g. if future cuttings mainly involve thinning, the potential available reserve of bioenergy might not increase as much as if most of the cuttings were final fellings (Kärkkäinen et al. 2008). Furthermore only a part of the maximum biomass potential is recoverable. Many technological, economical, socioeconomic and environmental factors affect the availability of forest biomass (Hakkila 2004). Probably the most important factors are the price development of alternative fuels, procurement technology and logistics, quality requirements of forest chips, silvicultural recommendations, the extent to which forest owners choose to engage in biomass recovery as well as the energy and climate policies at the national and international levels (Hakkila 2004).

Hakkila estimated (2004) that the technically harvestable annual biomass potential in Finland was 15 million m³, which represented 33% of the 45 million m³ theoretical annual potential. The theoretical potential consisted of logging residues left in the forest after cutting and the small-tree biomass, which in thinnings of young stands is removed, or should be removed, for silvicultural reasons. The theoretical annual potential was 16 million m³ from thinning and 14 million m³ from final fellings. In addition, the theoretical potential of stumps and roots from final fellings was 15 million m³. According to Laitila et al. (2008) the technically harvestable annual biomass potential was 15.9 million m³. The technically harvestable potential consisted of 6.9 million m³ of whole trees from early thinning, 6.5 million m³ of logging residues from final fellings and 2.5 million m³ of spruce stumps from final fellings.

1.2.3 The supply potential of forest chips in 2020

Metsäteho Oy and Pöyry Energy Oy carried out a study to produce an analysis of the possibilities of increasing the usage of wood-based fuels in Finland by 2020 (Kärhä et al. 2010). The research created two different scenarios for the forest industry production of the year 2020: the basic scenario and the maximum scenario. The roundwood consumption and demand of the forest industry were based on these scenarios. Domestic industrial roundwood cuttings were 57 million m^3 in the basic scenario and 68 million m^3 in the maximum scenario in 2020. The research was carried out at the boiler and supply source levels. The cuttings by Forestry Centre and further by municipality in 2020 were allocated with the MELA software by applying the 10^{th} National Forest Inventory data of the Finnish Forest Research Institute. The harvesting conditions for recovery sites were created by applying the stand data of Metsäteho Oy. Pöyry Energy's databases enabled research into the usage of wood-based fuels in the study (Kärhä et al. 2010).

The study determined three different levels of potentials. *The gross potential* was the amount of logging residues and stumps that are produced in regeneration cutting areas and whole trees produced when cutting operations in young stands are carried out on time. *The techno-ecological* supply potential was the harvestable forest chip material raw base, when the following limitations were taken into consideration: the recommendations of the guide for energy wood harvesting were followed (Koistinen & Äijälä 2005), integrated harvesting of pulpwood and energy wood was carried out when the yield of pulp wood was more than 20 m^3 ha^{-1} and the degree of recovery at the cutting area were 70% for logging residues, 95% for whole trees and 85% or 80% for spruce, birch and pine stumps. Furthermore the private forest owners' willingness to sell was 90% for logging residues, 70% for stumps and 80% for whole trees (Kärhä et al. 2010). *The techno-economical* usage included the total supply costs of forest chips and the amounts that energy plants were willing to pay for the chips. In that calculation, the price of emission rights was 30 € t^{-1} CO_2 and the subsidy for chips from small-diameter thinning wood from young forests was set to 4 € MWh^{-1}.

The gross potential of forest chips was 105 TWh in the basic scenario and 115 TWh in the maximum scenario of the research (Kärhä et al. 2010). Correspondingly, the techno-ecological supply potential was 43 TWh in the basic scenario and 48 TWh in the maximum scenario in the year 2020. The proportion of whole trees from thinning was 51% of the gross potential in the basic scenario and 46% in the maximum scenario. In the techno-ecological supply potential the corresponding proportion of whole trees was 37% in the basic scenario and 33% in the maximum scenario.

According to the study, the areas with the greatest theoretical (gross) and techno-ecological supply potential were Lapland, North Ostrobothnia, North Karelia, North Savo and South Savo. The biggest technical utilisation potential of solid wood fuels was located in South-East Finland and it was the lowest in the provinces of Kainuu, South Ostrobothnia, South Savo and North Karelia (Kärhä et al. 2010).

In the techno-economical potential the proportion of logging residue chips and stump wood chips increased and the proportion of more expensive whole-tree chips decreased (Kärhä et al. 2010). In the basic scenario the techno-economical harvesting potential of whole trees was 7.4 TWh, logging residues 10.3 TWh and stumps 9.2 TWh. In the maximum scenario the techno-economical harvesting potential of whole trees was 6.4 TWh, logging residues 12.8 TWh and stumps 10.1 TWh (Kärhä et al. 2010).

1.3 Wood procurement in Finland

1.3.1 Procurement system and machinery

The three largest forest industry companies – Stora Enso, UPM and Metsä Group – are responsible for the procurement of more than 80% of all commercial timber in Finland (Finnish Statistical Yearbook... 2010). They operate nationwide and perform their wood procurement through special forestry departments that contract the harvesting work to independent entrepreneurs. Nowadays about 99% of the harvesting is mechanised, but the most sensitive and demanding sites are felled motor-manually (Finnish Statistical Yearbook... 2010). Cutting and forwarding are included in a single logging contract, whereas secondary transport is usually subject to a separate contract. A forestry contractor typically owns 1–6 forest machines or trucks (MetsäTrans 2011). In 2009, 1120 timber trucks, 1640 forwarders and 1590 harvesters were employed in roundwood procurement in Finnish forests (Finnish Statistical Yearbook... 2010).

The average logging costs of roundwood were 10.44 € m^{-3} and transporting costs were 7.57 € m^{-3} in 2009 (Finnish Statistical Yearbook... 2010, Kariniemi 2010). The average overhead cost was 3.51 € m^{-3} (Kariniemi 2010). In the year 2009, 13% of mechanically harvested roundwood originated from first thinnings, 27% from later thinnings and 60% from regeneration fellings (Finnish Statistical Yearbook... 2010). The total average transportation distance was 171 kilometres (Kariniemi 2010).

In the year 2009, 70% of the timber transported was brought to the mill directly by road. Rail transportation accounted for 26% of the timber volume, and waterway transportation for 4% (Kariniemi 2010). Railway and water transportation also includes truck haulage from the forest to the railway terminal, water storage point or harbour. In the year 2009 the average transportation distances were 317 km by rail, 344 km by floating, 246 km by barge and 109 km by truck directly to the mill. The corresponding unit costs were 3.1 cents m^{-3} km for rail transportation, 2.7 cents m^{-3} km for floating, 4.1 cents m^{-3} km for barge transportation and 6.1 cents m^{-3} km for truck transportation (Kariniemi 2010).

In Finland, timber procurement is based on the cut-to-length (CTL) method both in thinnings and regeneration cuttings. In the CTL method, both delimbing and crosscutting into assortments are carried out at the stump and timber is transported, off the ground, to the roadside landing by load-carrying tractors (Hakkila 1995, 2004, Uusitalo 2010). The modern CTL method normally uses two machines: a harvester and a forwarder. Forwarding to the roadside, where the timber is temporarily stored, sorted and piled for secondary transport, is commonly performed using a medium-size forwarder weighing 11 to 13 tonnes with a payload capacity of 10 to 12 tonnes (Sirén and Aaltio 2003, Uusitalo 2010). Purpose-built forwarders are normally equipped with a 10-m hydraulic crane. The width of the 6- or 8-wheel machine is about 2.7 m. According to Rieppo (2001), due to the increasingly robust structure of forwarders, the common and somewhat harmful trend is that the weight of the forwarder grows whereas the payload capacity remains unchanged.

A modern harvester uses both wireless communications and satellite positioning (Key to the Finnish…2006, Uusitalo 2010). Precise data on the area marked for logging and wood categories ordered are transferred directly from the forest company's information system to the computer of the harvester. Running so-called marking for cutting software, the computer optimises the value of every stem felled. Taking the shape of the stem into account, it calculates the most economical lengths into which to cut it (Key to the Finnish…2006, Uusitalo 2010).

Cutting and location data are transmitted wirelessly to the procurement organisation. The ability to anticipate changes in demand and buy in a sufficient reserve of wood is a vital requirement in procurement (Key to the Finnish…2006, Uusitalo 2010). A reserve is the amount of standing wood that a mill has bought. Actual stockpiles of felled wood at mills or in piles by the roadside are generally small. For mills to be able to respond rapidly to customers' needs, wood must be transported quickly and flexibly (Key to the Finnish…2006, Uusitalo 2010). Information technology has stepped up efficiency in not only wood harvesting, but also its transportation by road or otherwise. Efficient management of flows to mills requires investment in the transport equipment. Computers in vehicles, optimised run schedules and satellite positioning make wood transport more efficient and reduce costs (Key to the Finnish…2006, Uusitalo 2010). Modern forest machines are also often equipped with on-board monitoring solutions, which enable novel opportunities for operator training and forest machine maintenance (Peltomaa and Shackelton 2011).

1.3.2 The timber assortments

From five to ten categories of wood, each with its own length, diameter and quality requirements, can be cut from a single species. The knotless lower trunk of a tree is its most valuable part. Thick, straight stems, over 15 cm in diameter, are mainly used in sawmills or to make wood panels. Thinner stems and those that are unsuitable as saw logs are used to make chemical and mechanical pulp (Hakkila 1995, Key to the Finnish…2006, Uusitalo 2010). Small trees, stumps, branches and crowns can be burned to generate energy. The dimensional requirements of timber depend on the end product, industrial process and the market situation. The individual requirements of companies may vary, but typically the minimum diameter is 15 cm for pine saw logs, 16 cm for spruce saw logs, 18 cm for birch veneer logs and 6–8 cm for pulpwood (Hakkila 1995, Key to the Finnish…2006, Uusitalo 2010).

Spruce pulpwood is used for the production of mechanical pulp for wood-containing printing papers (Hakkila 1995, Uusitalo 2010). Strict quality requirements are set for freshness and the lack of pathological infections. Even a small spot of rot leads to rejection and sorting the bolt into the pile of pine pulpwood (Hakkila 1995, Uusitalo 2010). Pine and hardwood pulpwood is used for sulphate pulping. Quality requirements are not especially strict and storage over the summer season is not uncommon (Hakkila 1995, Uusitalo 2010). A considerable part of the raw material of sulphate pulp is received in the form of process residue from sawmills and plywood mills (Hakkila 1995, Uusitalo 2010).

1.3.3 The purchase of timber assortments

The annual roundwood cuttings were 52 million m^3 in the year 2010 and of that volume 21.6 million m^3 were saw or veneer logs and 30.0 million m^3 were pulpwood (Simola and Suihkonen 2011). The bulk (40.7 million m^3) of the harvested roundwood volume was purchased from private forests, while a minority (11.3 million m^3) of the harvested volume originated from the forests of either forest companies or the State Forest Service (Simola and Suihkonen 2011). During the years 1998–2003, 53% of the roundwood sales agreements were made directly with the forest owners, 38% were made through the Forest Management Associations and 9% were made directly with the forest service customers of the forest companies (Ruohola et al. 2004).

In the year 2010 the average stumpage prices of logs were 54 € m^{-3} for pine, 55.3 € m^{-3} for spruce and 39.4 € m^{-3} for birch. The average stumpage prices of pulpwood were 15.5 € m^{-3}

for pine, 18.6 € m^{-3} for spruce and 15.5 € m^{-3} for birch (Sevola and Ollonqvist 2011). In first thinnings the stumpage price is usually lower than in later thinnings and final fellings because of high wood procurement costs resulting from small stem size and low removal per hectare (e.g. Heikkilä et al. 2007). Roundwood from private forests was mainly purchased standing (34.5 million m^3), while 6.2 million m^3 were purchased for delivery (Simola and Suihkonen 2011). The average roadside prices of logs were 56.3 € m^{-3} for pine, 55.7 € m^{-3} for spruce and 42.5 € m^{-3} for birch. The average roadside prices of pulpwood were 26.4 € m^{-3} for pine, 29.4 € m^{-3} for spruce and 26.8 € m^{-3} for birch (Sevola and Ollonqvist 2011).

The supply of forest chips, especially logging residues and stumps, is closely tied to the purchase of roundwood, because branches and stumps are primarily collected as a by-product of industrial timber from final fellings. An exception to this rule are early thinnings where fuel is the primary product and pulpwood only a side product, if at all it is recovered. The stumpage price of forest chips is just nominal compared to roundwood (Laitila et al. 2010b) and therefore the recovery of wood biomass is encouraged especially by promoting the benefits gained in silviculture and forest regeneration (Ryymin et al. 2008). The sale agreement specifies the prices of timber assortments, harvesting schedule, storing, transporting and recovery of energy wood. A common rule is that the roundwood buyer harvests the energy wood and hauls it to the roadside landing but the harvesting option can also be conveyed to a third party if the forest owner requires or accepts this (Ryymin et al. 2008).

1.4 The production of forest chips from young stands

1.4.1 Systems of chipping and transporting

Comminution is the primary element of the forest chip supply chain affecting the whole system (Asikainen 1995), because the location where comminution is performed determines the form of the material to be transported. When the comminution is done at the end-use facility or at the terminal, the comminution is conducted in a centralised area and off-road transportation is followed by long-distance transportation. In a system where comminution takes place at the roadside landing, it and long-distance transportation are linked to each other. In the terrain comminution system, forwarding and comminution work phases are conducted by a single machine in one pass (Ranta 2002).

Centralised comminution at the end-use facility or at the terminal enables the efficient use of comminution machines that are either stationary or mobile. If raw material is transported in an unprocessed form, it results in low bulk density and therefore higher transportation costs compared to pre-processed, comminuted, delimbed or bundled material. In Finland the payload is usually limited by the bulk volume rather than the legal mass capacity (Ranta and Rinne 2006). Comminution and long-distance transportation are independent of each other, which results in a high degree of capacity utilisation and thus relatively low comminution costs. However, extensive investment in the centralised comminution system presupposes full employment and large annual comminution volumes (Asikainen et al. 2001).

Comminution will approximately double the bulk density of the transported material (Angus-Hankin et al. 1995) and thus significantly reduce the transportation costs. When the comminution is done at the landing, the chipper and truck are dependent on each other and some part of the working time of the chippers or chip trucks may be wasted in stoppages or waiting (Asikainen 1995). The idling time reduces the operational efficiency of the supply chain and increases costs. If interchangeable containers are used, waiting and queuing can also occur, but the associated problems are normally smaller (e.g. Routa et al. 2012). In the case that chips are blown directly onto the ground or snow, which is a commonly used practice in Sweden, a separate loader or a bucket crane on the chip truck is used to load the chips, and interference between the different units within the supply chain is insignificant (Thorsén et al. 2011).

Recently, chipper trucks, i.e. chip trucks that include a chipper unit, are quickly gaining popularity in Sweden (Thorsén et al. 2011). When the chipper-truck system is used, system waiting and queuing are eliminated. These advantages are gained at the expense of increased capital commitment and lower payload (Thorsén et al. 2011). The chipper-truck blows the chips directly into containers or a conventional cargo hull and then hauls the load to the plant. As only a single unit is needed, the chipper-truck is suitable for small sites and for delivering chips to small heating plants (Hakkila 2004, Thorsén et al. 2011).

A terrain chipper is heavier and more expensive than a forwarder; furthermore, the payload is quite small and hence the forwarding distance must be short and the ground has to be flat and firm (Ranta 2002). A terrain chipper is also more likely to experience technical failures and this also increases the harvesting costs (Ranta 2002). Furthermore, high snow or water content in the wintertime might spoil the heating value of fuel chips.

In Finland the procurement of small-sized thinning wood chips is mainly based on chipping at the roadside storage point (73%) or at the terminal (24%) (Kärhä 2007a). Comminution at the end-use facility is not so common in thinning wood harvesting compared to logging residue or stump wood chip production. Comminution at the landing is a suitable and quite cost-competitive procurement system for power and heating plants of all size categories. Terminals operate as buffer storage facilities, enabling a more secure supply of fuel chips and also serving as a process management tool for the whole supply chain. The use of a terminal is also a compromise between comminution at the landing and at the plant (Vartiamäki et al. 2006). The raw material is transported in an unprocessed or a pre-processed form to the terminal and delivered to the plant as chips. Comminution in the terrain is a seldom-used harvesting method in Finland (Kärhä 2007b), especially in pre-commercial thinning wood operations.

In the study of Metsäteho, the industrial forest chip suppliers estimated that the role of chipping at the plant in the production of chips from small-sized thinning wood will increase in the future (Kärhä 2011a). The study also predicted that the proportion of terminal chipping in the production of chips from small-sized wood will remain high in the future. Conversely, it was predicted that the proportion of roadside chipping will decrease (Kärhä 2011a).

The users of forest chips are mainly local district heating or combined heat and power (CHP) plants and the average transportation distances are shorter than for industrial timber assortments. Therefore trucks dominate energy wood transportation (Kärhä 2011a) and at the present time there are only a few large CHP installations that can even use railway or waterway transportation (Karttunen et al. 2008, Tahvanainen and Anttila 2011). The demand for fuels is largest in Southern, Western and Central Finland, while the production potential is located more in Eastern and Northern Finland (Laitila et al. 2010b, Kärhä et al. 2010). Disturbances in local fuel supply and the need for balancing the regional supply and demand during periods of peak consumption require efficient systems for long-distance transportation of biofuels. Planned large-scale production of liquid biofuels and the development of the so-called biorefinery concept may also increase the need for long-distance transportation of energy wood (Tahvanainen and Anttila 2011).

Current legislation on the physical dimensions of the truck-trailer combination limits total length to 25.25 m, width to 2.55 m and height to 4.2 m (Ranta and Rinne 2006). Weight restrictions limit gross vehicle weight to 60 tonnes (Ranta and Rinne 2006). A truck can usually carry a payload of 43–44 m³ of chips, 25–30 m³ of loose whole trees, 47–48 m³ of pulpwood or multi-stem delimbed shortwood, and 42–48 m³ of whole-tree bundles (e.g. Laitila 2008, Laitila et al. 2009, Laitila et al. 2010b, Jylhä et al. 2010, Kärhä et al. 2011, Laitila and Väätäinen 2011, Jylhä 2011).

In 2007 (Kärhä 2011a) the estimated number of chip trucks in use was 130 units, with a portion of the chip trucks also used for transporting energy peat and industrial wood by-products. About 60 energy trucks were equipped for transporting loose logging residues, whole trees and stump wood. Loose material trucks are typically purpose-built with a solid bottom and sideboards around the load space to prevent material from falling out during transport. The bundling system (Johansson et al. 2006, Jylhä and Laitila 2007, Laitila et al. 2009, Jylhä et al. 2010, Kärhä et al. 2011, Jylhä 2011) and multi-stem delimbed shortwood (Laitila et al. 2010a, Laitila and Väätäinen 2011) enable the use of standard timber trucks for transportation.

In the study of Tahvanainen and Anttila (2011) railway transportation was compared to the most commonly used truck transportation options in long-distance transport. The potential for the development of supply chains was analysed using a sensitivity analysis of 11 modified supply chain scenarios. For distances shorter than 60 km, truck transportation of loose residues and end-facility comminution comprised the most cost-competitive chain. Over longer distances, roadside chipping with chip truck transportation was the most cost-efficient option. When the transportation distance increased from 135 to 165 km, depending on the fuel source, train-based transportation offered the lowest costs. The most cost-competitive alternative for long-distance transport included a combination of roadside chipping, truck transportation to the terminal and train transportation to the plant.

1.4.2 Controlling the operation of harvesting of forest chips

Where the procurement of energy wood has been integrated into industrial wood procurement, largely the same supply chain management applications as those used in purchasing, harvesting and transporting industrial wood are used in the controlling of harvesting and transportation of energy wood (Asikainen et al. 2001). The resources available to fuel-chip enterprises for investing in costly data processing systems are limited (Sikanen et al. 2004), while, on the other hand, the steering of functions is simpler than it is in the procurement of industrial wood. Indeed, plentiful use is made of Internet-based GPS software and conventional paper maps in the procurement of forest chips. The parties involved in procurement also exchange information by means of mobile phones (Seppänen et al. 2008).

The amount of information needed in the procurement of energy wood is comprehensive and operations must remain on schedule (Seppänen et al. 2008, Windisch et al. 2010). The stores of energy wood need to be chipped at the right time to ensure the quality of the chips, and the chips must be delivered at the right time to the appropriate end-use facilities. Furthermore, the roadside storage points must be accessible throughout the delivery period. When appointing the chip supplier, the reliability of deliveries is an important criterion from the viewpoint of the end user of the chips. Capital is tied up in the stored raw material due to be chipped, and this, along with quality, imposes its own demands on the turnover rate of the material in storage (Seppänen et al. 2008). It is essential from the point of view of the planning of the procurement operations that the parties involved in the procurement chain are provided with the details of the harvesting targets well in advance. A challenge of its own in chipping lies in the uneven distribution of the work. During the cold season of the year, the chipping machinery and transportation equipment are in intensive use, while during the summer months the problem is lack of work.

Mutual exchange of information among the parties concerned is important in networking. The incompatibility of the various parties' data processing systems and the lack of information standards have been found to be the leading practical obstacles to the development of multiple customerships and networking between business partners (Räsänen 2007). Different parties cannot relay data and messages to each other unless they have laid down common rules as to what the data mean and how they must be interpreted and processed. Non-standardisation in practical wood harvesting has often meant that entrepreneurs who have installed on their machines data processing systems that are compatible with the communications systems of only one customer have not been able to accept assignments from other customers because of the limitations of their data transmission. The parties involved can benefit from standardisation by creating interfaces for transmitting data and messages from one user to another and from one data processing system to another (Räsänen 2007). Wood procurement logistics, as well as procurement logistics focusing on forest chips, involve managing the delivery chain from the moment that a contract is signed up to the time of delivery of the material to the mill or power plant, and using data to steer operations throughout the chain.

The controlling of operations in the procurement of forest chips is also hindered by problems associated with the measurement of the amount and energy content of the material, and the measurement practices. The accuracy of measurement is often poor and the causes of its variation and magnitude are not known. When applying two-stage measuring, obtaining the final result can be unduly delayed (Hakkila 2006b). Moreover, the costs of measuring may rise excessively when considering the value of the material being measured, especially if several measurements are made at different stages of the delivery chain or if the ownership of the material changes between harvesting and end use (Lindblad et al. 2008, Lauhanen et al. 2010, Laurila and Lauhanen 2012).

1.4.3 Delivery and reception of the material

In a delivery chain based on roadside chipping, the time consumption of loading can be influenced by the choice of storage points and harvesting site arrangements as well as by the productivity of chipping. Ranta et al. (2002) conducted a study involving monitoring of chip-carrying trucks, and they found that a significant proportion of the time consumed by the trucks at the chipping site was spent on actions other than actual loading, e.g. driving at the storage point and turning. Consequently, a storage point should be such that the truck-trailer unit can be loaded without needing to detach the trailer or that the truck-trailer unit can be driven sufficiently close to the chipper unit and that moving the trailer is easy (Ranta et al. 2002). As regards the transportation of chips, the technique used in unloading the trucks and the size of the discharge bins at the receiving stations have a clear impact on the turnaround times of trucks at the power plant. The receiving station must be such that it is able to operate efficiently also when the power plant is running at full capacity (Ranta et al. 2002). Then rapid turnaround times at the power plant ensure steady fuel supply and better possibilities for the supplier to utilise the production equipment in a cost-efficient manner.

Problems in receiving chips at a heating plant or power plant are caused by slow turnaround times, inadequate storage facilities and queuing up of trucks at the discharge point. Chip trucks discharge their loads into storage silos by means of side-tipping or rear-tipping equipment. Non-chipped material is discharged directly into the crusher's in-feed platform or onto the storage area using either the truck's own loader or the receiving station's equipment. The delivery schedules in transportation are subject to rapid changes according to the changes in the weather and in the energy generated at the plant. Not all end-use facilities use preset schedules. Similarly, weighing, arrangements at the delivery point and sampling are in need of development. Furthermore, trucks delivering different materials use the same measurement and discharging services, and this means that different material flows and fuel mixture adjustments impact on one another. However, strict scheduling of deliveries is not rational in practice because factors such as weather conditions, which impact on transportation, make it almost impossible to achieve precise arrival times. It does, however, make sense to use scheduling to influence momentary fuel reception loads, such as during morning rush hours (Ranta et al. 2002).

A simulation study (Väätäinen et al. 2005) looked into the effect of the capacity of the chip receiving station on the truck's queuing time at a power plant in the town of Kuopio. The consumption of fuel at the power plant peaked at 72 trailer truck loads per day. The capacity of the discharge bin of the power plant in question was initially 146 $m^3 h^{-1}$ and in the comparison situation the capacity was raised to 200 $m^3 h^{-1}$. Thanks to improved operation of the receiving station, the average queuing time of the trucks was reduced from 65.5 minutes to 19.5 minutes. When, in addition to the above, scheduling was applied to steering of the transport of fuel material, the average queuing time was reduced from 43.5 minutes to 6.5 minutes.

The energy content of fuel material delivered to a power plant is a significant cost factor also from the logistics point of view. The energy content of forest chips is about 0.1 MWh less than that of peat per cubic metre (of bulk volume), and this means that the number of truck loads arriving at the power plant will increase when peat is replaced by forest chips. In the case of the Kuopio power plant, the number of truck loads arriving at the power plant increased by 1.5% when the proportion of forest chips was raised to 10% of the power plant's fuel consumption (Väätäinen et al. 2005). Similarly, when the proportion of forest chips was 50% of the fuel consumption, the number of truck loads increased by 6.3%.

1.4.4 Harvesting of energy wood as a separate operation

Mechanisation in the harvesting of energy wood from young stands has progressed rapidly. Less than ten years ago, this work was still done mainly motor-manually, while nowadays it is done almost entirely using mechanised solutions. The harvesting of energy wood can be either linked to the harvesting of industrial wood or carried out as a separate operation. When done separately from other wood harvesting, energy wood harvesting from young stands focuses on sites where the tending of the young stand has not been done at all or it has not been done well, and on sites where the nurse crop overlying a young stand needs to be removed. Yet another treatment situation where thinning for energy wood is a feasible alternative is a stand where the amount of pulpwood to be obtained is small though there is a clear need for thinning. Just as there are silvicultural recommendations pertaining to other wood procurement, there are silvicultural recommendations pertaining to the harvesting of energy wood (Äijälä et al. 2010). Among the matters dealt with in these recommendations are the target spacing of the retention stand by site type and tree species.

In the motor-manual cutting of whole trees, the chainsaw is equipped with a felling frame, which enables the user to make use of the kinetic energy of the falling tree in moving the stem in the desired direction, allowing the forest worker to keep his back straight. After cross cutting, the forest worker puts the chainsaw on the ground and grasps the falling tree. Using the momentum of the tree, he guides it onto the stack, placing the butt towards the strip road (Harstela and Tervo 1977, Hakkila et al. 1978). Piles can be located obliquely forwards, backwards or at right angles to the strip road, and on both sides of the strip road. Non-delimbed trees are gathered into sufficiently large piles (usually 2 to 6 stems) within a forwarder's crane reach and bucked to 6 to 8 m in length (Metsäteho 1991). When the distance between strip roads is 20 m, the most distant piles are located 8 or 9 m away from the strip road. The primary goal of the working technique is to combine felling and bunching instead of moving fallen trees to the bunch. Combined felling and bunching is applicable only to small-tree operations when the majority of the trees are smaller than 12 cm at breast height (Hakkila 1989).

Mechanised harvesting of small-diameter trees involves using a felling head designed for accumulating multiple trees or using a standard harvester head equipped for dealing with multiple trees (Heikkilä et al. 2005, Kärhä 2006, Kärhä et al. 2006, Laitila et al. 2010a,b). With a grapple that accumulates and carries out group processing of trees, it is possible to reduce grapple and boom motions and to improve the machine's productivity when compared to single-tree processing (Myhrman 1989, Lilleberg 1997, Brunberg 1998, Johansson and Gullberg 2002, Bergkvist 2003, Kärhä et al. 2005, Laitila and Asikainen 2006, Belbo 2011a,b). The trees are cross-cut using a cutting blade or a chainsaw. The tree bundle that is processed normally consists of 2 to 6 trees ($d_{1.3} < 10$ cm), and the number of small-diameter stems can be even higher. Removed trees are bunched alongside the strip road in piles consisting of several accumulated felling head bunches. The distance from the pile butt to the strip road is less than 1 m. After mechanised cutting, piles are located obliquely forwards with respect to the strip road. A light or medium-heavy harvester suitable for thinnings is used as the prime mover of the feller-buncher.

Another option available when planning mechanised harvesting of small-diameter trees is to use harwarders; these machines are capable of both felling and bunching as well as forwarding of small-diameter trees (Kärhä 2006, Kärhä et al. 2006, Laitila and Asikainen 2006, Rottensteiner et al. 2008, Belbo 2010). The competitiveness of harwarder is based on the large proportion of the cutting work in relation to forwarding and to the low transfer costs when compared to operating two machines (Kärhä 2006, Kärhä et al. 2006, Laitila and Asikainen 2006).

Forwarding energy wood from young stands to the roadside after motor-manual or mechanised cutting is carried out using forwarders designed for thinning operations (Kärhä 2006, Kärhä et al. 2006, II). Following storage and drying, the harvested stems are either chipped at the roadside prior to long-distance transportation or transported as such to a terminal or the end-use facility. The period of storage applied to thinning wood is usually one year, but even longer storage periods can be applied because storage-induced losses in dry matter are considerably less than those associated with the storage of material consisting of logging residues.

Thinning wood delivered to heating plants and power plants is comprised mainly of non-delimbed whole trees, but the harvesting of delimbed energy wood is one harvesting alternative alongside whole-tree harvesting (Heikkilä et al. 2005, Iwarson Wide 2009, Iwarson Wide and Belbo 2009, Laitila et al. 2010a, Laitila and Väätäinen 2011). A number of cutting devices equipped with delimbing knives and feed rollers that are suitable for multiple-tree processing are commercially available. Such multiple-tree processing equipment also enables the flexible use of harvesters in the harvesting of proper industrial wood and of energy wood while enabling the user to avoid having to invest in two separate purpose-made grapples. When processing energy wood, machines that include the delimbing function can be operated so that a desired amount of branch wood can be left on site without significantly impairing productivity (Heikkilä et al. 2005, Laitila et al. 2010a).

The harvesting costs of multi-stem delimbed shortwood are, on average, 23% greater than when harvesting whole trees (Heikkilä et al. 2005, Laitila et al. 2010a). The cost difference is caused by the difference in productivity; the harvesting cost differences decrease as the average dbh of the felled trees increases. Delimbing makes most sense on sites where the dbh of the trees to be felled is within the range of 9–13 cm and the stem size is within the range of 0.03–0.07 m^3. On sites dominated by broadleaves delimbing lowers productivity less than it does in stands of pine or spruce. This is mainly explained by the fact that delimbing reduces accrual in broadleaf-dominated stands less than it does in pine or spruce stands. Furthermore, delimbing stems that have hardly any branches is speedy and often all that is needed to finish the processing of a stem free of branches is to cut off the top.

Forwarding multi-stem delimbed shortwood to the roadside is slightly more efficient than whole-tree forwarding and the costs of multi-stem delimbed shortwood forwarding were 13% lower than those of whole-tree forwarding (Heikkilä et al. 2005, Laitila et al. 2010a). The difference is largely caused by the increase in payload when forwarding delimbed wood. When harvesting multi-stem delimbed shortwood, it is also possible to achieve savings and to add to the accrual of forest chips as the delimbing of energy wood can extend harvesting operations to sites where the aim has previously been to avoid whole-tree harvesting because of the possible resultant growth disturbances and increment losses likely due to loss of nutrients. Examples of such sites are stands of spruce, peatland sites and nutrient-poor mineral soils (Äijälä et al. 2010).

Close to 200 harvesters were operated in energy wood harvesting operations in 2007, and most of these machines were also used in the harvesting of industrial wood (Kärhä 2007b). More than half of these machines were equipped with an initially standard harvester head that had been modified to adapt it to the harvesting of energy wood. In less than half of the machines, the harvester head had been replaced with an accumulating feller-buncher head for the duration of the harvesting of energy wood. The advantage of feller-buncher heads is that they are cheaper than standard harvester heads. This is explained mainly by their simpler structure and technology. The use of standard harvester heads is supported by the fact that the investment required to modify an existing head to suit another kind of work amounts to just a few thousand euros.

In 2007, some 300 medium-heavy and heavy forwarders were used in forwarding stumps, logging residues and whole trees to the roadside. One in five of these machines was used solely for forwarding energy wood to the roadside. Forwarding of energy wood was of secondary importance to most of the entrepreneurs; their principal source of earnings was the forwarding of industrial wood. It is estimated that there were 70 harwarders in use in the harvesting of energy wood in 2007 (Kärhä 2007b). One in five of these machines was used solely for harvesting and forwarding energy wood to the roadside.

In Sweden, practically all large-scale fuel procurement from young stands is carried out by mechanised harvesting (Brunberg 2011, Thorsén et al. 2011, Routa et al. 2012). The predominating system is a one-grip thinning harvester with accumulation equipment producing roughly delimbed tree-sections, while terrain transport is carried out by a conventional forwarder. Simpler felling heads are also used, but mainly on infrastructural objects such as roadsides and powerlines, and the volumes are comparatively small (Brunberg 2011, Thorsén et al. 2011, Routa et al. 2012).

1.4.5 Integrated harvesting of industrial wood and energy wood

A method whereby industrial wood and energy wood are harvested simultaneously has rapidly found widespread use in operations involving first thinnings (Kärhä et al. 2009, Kärhä 2011b). The purpose of integrating wood harvesting or wood procurement is to achieve reduced overall procurement costs compared to the separate procurement of industrial wood and energy wood while at the same time extending the raw material base of forest chips into conventional commercial wood harvesting operations (Kärhä et al. 2009, Kärhä 2011b).

There are two ways to implement integrated wood procurement. The more common method is what may be called the "Two Stacks Method" in which industrial wood is stacked separately from stacks of either delimbed or non-delimbed thinning wood that does not fulfil the requirements applied to industrial wood (Kärhä et al. 2009, Kärhä 2011b, Lehtimäki and Nurmi 2011).

Following forwarding to the roadside, the industrial wood fraction is delivered to the pulp and paper industry while the energy wood fraction goes to energy generation plants (Kärhä et al. 2009, Kärhä 2011b). An absolute precondition for integrated wood harvesting is that the harvester head includes multiple-tree processing and delimbing functions. The capability to accumulate small trees in the grapple improves the efficiency of wood harvesting, and the general quality requirements of industrial wood presuppose the delimbing of the pulpwood fraction. In practice, the accumulating function can nowadays be retrofitted to all commercially available harvester heads by means of either a piece of accessory equipment or a software update. The results of research (Kärhä and Mutikainen 2008) show that, in first thinnings, the cutting productivity of the Two Stacks Method is about 10% lower than the productivity of whole-tree cutting. The accrual of industrial wood and energy wood can be influenced by changing pulpwood cross-cutting lengths, quality requirements and minimum top diameter in line with the market situation and harvesting conditions. The accrual and the number of timber assortments also has a significant impact on forwarding productivity and cost (Nurminen et. al 2006, Iwarson Wide 2011).

The other way of implementing integrated harvesting of industrial wood and energy wood is the "Fixteri Method", which makes use of multiple-tree processing and bundling techniques (Jylhä and Laitila 2007, Kärhä et al. 2009, Laitila et al. 2009, Jylhä et al. 2010, Nuutinen et al. 2011, Jylhä 2011). In this new method for harvesting wood of industrial dimensions, the harvested trees are bound into tight bundles along with the branches and foliage. The pulpwood bundles are then transported to the debarking section of a pulp mill where the industrial wood and energy wood fractions are separated from one another (Kärhä et al. 2009, Jylhä et al. 2010, Kärhä et al. 2011, Jylhä 2011). In addition to bundles with pulpwood-dimensioned trees, separate energy wood bundles consisting of undersized trees and unmerchantable tree species can be produced for use in energy generation at power or heating plants (Kärhä et al. 2009, Jylhä et al. 2010, Kärhä et al. 2011, Jylhä 2011).

Transportation can be arranged using standard forwarding equipment and long-distance transportation equipment (Kärhä et al. 2009, Laitila et al. 2009, Jylhä et al. 2010, Kärhä et al. 2011, Jylhä 2011). The bundles are, on average, 2.7 m in length, 0.65 m in diameter and 0.5 m^3 in volume (Jylhä and Laitila 2007, Kärhä et al. 2009, Laitila et al. 2009, Jylhä et al. 2010, Nuutinen et al. 2011, Jylhä 2011). This recently developed method is suitable for large-scale wood procurement by industrial enterprises, and its competitiveness is based mainly on the savings to be achieved in forwarding to the roadside and long-distance transport, and on the chipping of the energy wood fraction being combined with drum-debarking of the industrial wood fraction (Kärhä et al. 2009, Jylhä et al. 2010, Kärhä et al. 2011, Jylhä 2011).

In a study conducted by Metla and Metsäteho (Kärhä et al. 2009), the costs of the bundling-based production chain for whole trees were calculated and then compared with the costs of alternative production chains used in the procurement of energy wood and small-diameter industrial wood from first thinnings. The lowest wood procurement costs were achieved when applying integrated procurement of industrial wood and energy wood using the aforementioned “Two Stacks Method”. The overall costs of whole-tree chips were also competitive in integrated procurement. The procurement costs of the fuel chips made from bundles of energy wood were clearly higher than the procurement costs of whole-tree chips harvested either separately or integrated with other harvesting.

In the case of harvesting of small-diameter wood from thinnings, the differences between the harvesting methods are decided at the cutting stage, and any cost differences arising at that time are difficult to make up for later on, especially when operating within reasonably short forwarding and long-distance transportation distances (Kärhä et al. 2009, Jylhä et al. 2010, Laitila and Väätäinen 2011). The comparison calculations indicated that the competitiveness of bundling of whole trees increases with decreasing average stem size of the first-thinnings pulpwood (Kärhä et al. 2009). On the basis of the study, it can be said that the optimal sites for applying bundling of whole trees are first-thinnings stands where the average dbh of the removed trees lies within the range of 7 cm–10 cm. The relative advantage of bundling whole trees lies in the combined procurement of pulpwood and energy wood. The cost calculations showed that the cost-competitiveness of the bundling of whole trees when harvesting only energy wood is poor (Kärhä et al. 2009, Laitila and Väätäinen 2011).

1.4.6 The cost-competitiveness of fuel chips from young stands

The recovery of logging residues and stumps from final fellings is more cost-competitive than harvesting small trees from early thinnings (Ryymin et al. 2008, Laitila et al. 2010b). The difference in the production cost is caused by the high cost of cutting of small trees, whereas in off- and on-road transportation as well as in comminution the cost differences between logging residues, stumps and energy wood from thinnings are rather small (Ryymin et al. 2008, Laitila et al. 2010b).

In the harvesting of logging residues the piling of tops and branches is integrated into the cutting of round wood by changing the working method in order to allow logging residues to pile up along the strip road whereas in the normal method the branches and tops are collected on the strip road in order to protect the soil and to improve the bearing capacity of the ground (Brunberg 1991, Wigren 1991, Wigren 1992, Nurmi 1994). According to several studies the piling of logging residues only has a nominal effect on the cutting and forwarding productivity of industrial roundwood, whereas the integrated working method significantly improves both the yield and recovery of logging residues, thereby reducing harvesting costs (Brunberg 1991, Kärhä 1994, Asikainen 1995, Nurmi 2007).

In stump harvesting the volume of harvested stumps is considerably bigger compared to trees from early thinning, which improves productivity and reduces costs (Ryymin et al. 2008, Laitila et al. 2010b). Furthermore, in clearcut areas the protecting of standing trees does not limit the productivity of the stump harvester and the operating hour costs of an excavator-based stump harvester are also somewhat lower compared to those of a medium-size thinning harvester (Ryymin et al. 2008, Laitila et al. 2010b).

Small stem sizes, low removals per hectare, dense undergrowth and difficult terrain on the harvesting site all result in low productivity and high cutting costs in early thinnings (Kärhä et al. 2005, Kärhä 2006, Laitila 2008, Oikari et al. 2010, Petty & Kärhä 2011). In Finland, typical harvesting conditions in early thinning involve a stand where harvesting intensity amounts to approximately 40–70 m^3 ha^{-1} and the stem size of the harvested trees in terms of breast height diameter ($d_{1.3}$) is less than 10 cm (Kärhä 2006, Kärhä et al. 2006, Laitila 2008).

1.4.7 The Kemera subsidy system

Between 2009 and 2010, the mean price of forest chips paid at the gate of energy plants has varied between 16.5 and 19.7 € MWh^{-1} in Finland (Polttoaineiden hintaseuranta… 2010, Petty and Kärhä 2011). However, when producing whole-tree chips from young stands, the total production costs are 20–25 € MWh^{-1} (Laitila 2008, Kärhä et al. 2009). In order to promote silvicultural thinnings and increase the production of small-sized wood chips in young stands, the Finnish government provides production subsidies for wood chips of small-diameter stems from early thinnings, as set out in the Sustainable Silviculture Foundation Law "Kemera" (Kestävän metsätalouden rahoituslaki 2007, Lauhanen et al. 2010, Petty and Kärhä 2011). Several studies have found that, as a whole system, the profitability of production of small-diameter thinning wood chips from young stands is minimal without the Kemera subsidies (Kärhä 2002, Vasara 2006, Helynen et al. 2007, Ahtikoski et al. 2008, Petty and Kärhä 2011). Neglecting silvicultural thinning may also endanger the future roundwood supply of the forest industries, especially that of saw and veneer logs (e.g. Heikkilä et al. 2007, Jylhä et al. 2010).

The Kemera subsidy is provided only for young forest stands owned by non-industrial private forest owners in Finland (Laki kestävän metsätalouden… 1996, Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008). The subsidy is paid for work by non-industrial private forest owners as well as for contracted work. To be eligible for the subsidy, the area of the stand used when applying for the subsidies must be greater than 1 ha (Laki kestävän metsätalouden… 1996, Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008). A principal element in the Kemera incentive system is that financial support may only be granted once throughout a stand's rotation cycle (Laki kestävän metsätalouden… 1996, Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008). Currently (spring 2012) there are four subsidy instruments offered for thinning young forest stands for energy in the Kemera incentive system (Finland's National Forest… 2008):

I Subsidy for thinning young stands,

II Subsidy for small-sized energy wood harvesting,

III Subsidy for chipping, and

IV Subsidy for providing work clarification.

Financial support is paid for thinning operations in stands of the second development class, where there is no immediate need for industrial roundwood harvesting, such as first thinning, and the harvested wood is used for energy generation (Laki kestävän metsätalouden… 1996, Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008). In the case of trees with a stump diameter greater than 4 cm, more than 1000 trees per hectare must be removed and the total energy wood removal must be greater than 20 m^3 at the stand (Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008). The Kemera subsidy is separated into three geographical zones, which are Southern Finland, Central Finland and

Northern Finland. The subsidy for thinning young stands varies between different zones; the highest financial support is provided in Northern Finland (Laki kestävän metsätalouden… 1996, Kestävän metsätalouden rahoituslaki 2007, Finland's National Forest… 2008).

Petty and Kärhä (2011) calculated the maximum Kemera subsidies granted for a stand in each subsidy zone with a stand size of 3.0 ha and whole-tree removal of 50 m^3 ha^{-1}. The maximum total Kemera subsidies available vary between 917–833 € ha^{-1} depending on the subsidy zone where the stand is located. According to Petty and Kärhä (2011) the maximum total subsidies per harvested cubic metre would be approximately 16.7–18.3 € m^{-3} or 8.3–9.2 € MWh^{-1} if 1.0 solid cubic metre of wood corresponds to 2.0 MWh of energy in the conversion. The largest subsidy instruments are: Subsidies for small-sized energy wood harvesting, subsidies for thinning young forest stands and subsidies for chipping. Subsidies provided for the certification of the fulfilment of the work contract are relatively minor in comparison to the other instruments (Finland's National Forest… 2008, Petty and Kärhä 2011).

With reasonable government incentives put in force, energy wood from e.g. young stands can be converted into a competitive energy source. The dilemma is, however, how to value the purported benefits associated with bioenergy such as decrease in greenhouse gas emissions, increased security of energy supply and support for the development of rural communities (Ryan et al. 2006). If these evident benefits are left unvalued, then bioenergy might not be as competitive as anticipated with other energy sources (Schneider and Kaltschmitt 2000, Ryan et al. 2006). Furthermore, the costs of subsidising the price difference between bioenergy and fossil fuels can be viewed as CO_2 emissions saved, which is mainly a political, not purely an economical, issue (Ahtikoski et al. 2008). This fact complicates administrative action such as allocating subsidies and tax tools (Ahtikoski et al. 2008).

1.5 Drivers behind the current research

The use of forest chips is increasing fast. The evaluation of the energy wood potential requires forest resource information that is accurate enough, particularly concerning the variation of young forest stands. For decision making in forest energy policy, we have to be able to estimate the availability and cost of a specific amount of raw material that is procured to a certain place of utilisation. Forest fuels are accepted and welcomed by all parties, but environmental constraints, such as effects on biodiversity and increased nutrient loss, are still under discussion and debate. Several logging systems and supply chains have been introduced for forest fuels and their cost-competitiveness differs depending on the conditions where they are being used. The selection of suitable harvesting methods calls for information on the effect of conditions at the logging sites on productivity and costs.

From a forest fuel user's point of view the availability of forest fuels, the reliability of deliveries, cost-competitiveness and quality of fuel as assessed in terms of the combustion process are the most substantial factors controlling the usage of forest fuels (Ranta 2002). As the harvested quantity increases, forest fuels must be recovered over a larger geographic area. The operations have to be extended to more and more difficult stand conditions and distant locations (Asikainen et al. 2001, Ranta 2002, Hakkila 2004). Knowledge of cost factors is required to both direct harvesting to feasible logging sites and plan operations. When starting or increasing the use of forest fuel, there is an obvious need for suitable analysis tools (Laitila 2006). In practice the plant-level estimates of the potential for utilising biomass for energy should be made by first developing supply curves that show how much biomass can be obtained at various cost levels from each source (Ranta 2002). In order to further improve the calculation of costs, studies on the productivity of functions such as cutting, forwarding, chipping and transporting should be carried out, and productivity functions should be formulated (Anttila et al. 2011). For calculating the costs of machines and vehicles, detailed data on variable and fixed costs should be collected as well (Harstela 1993, Anttila et al. 2011).

1.6 Objectives of the research

The primary aim of the present study is to develop a methodology for estimating the procurement cost of forest chips from early thinnings. The methodology employs time consumption functions, productivity parameters and cost factors of various phases of the sub-operations (e.g. management, cutting, forwarding, chipping, transporting) included in the production systems. The wood procurement cost data is linked with worksite conditions and wood availability in order to obtain reliable information for choosing a harvesting method for energy wood procurement from young stands. The most common logging systems and supply chains of forest chips used in early thinnings in Finland are compared at stand and regional level using productivity models and cost parameters obtained mainly from the sub-studies of this thesis. In addition a decision tree is formed of the various factors impacting on the choice of an economically, ecologically and socially sustainable harvesting method for energy wood from young stands. More specifically, the objectives of the sub-studies (Study I–IV) were as follows:

1) To describe the work pattern of the energy wood harwarder, create time consumption models for energy wood logging when using the harwarder method and estimate the logging productivity of the harwarder (**Study I**).

2) Compare forwarding productivity following motor-manual and mechanised cutting of whole trees and create productivity models for forwarding as above (**Study II**).

3) Compare and analyse the most common logging systems and supply chains of forest chips at stand level that are used in early thinnings in Finland by using existing productivity models and cost parameters. The compared logging systems were: the motor-manual and mechanised cutting of whole trees and forwarding by the forwarder and logging of whole trees by the forwarder-based harwarder (**Study III**).

4) Compare, at regional level, the harvesting alternatives, available volumes and procurement costs of small-diameter thinning wood chips for fuel, when harvesting trees as either multi-stem delimbed shortwood or whole trees and when the logged trees are chipped at the roadside landing. The analyses were performed as simulated treatments in young stands based on existing productivity and cost functions and yield calculations of the sample plots of the 9th National Forest Inventory of Finland (**Study IV**).

5) Create the decision hierarchy for selecting the method for harvesting energy wood from young stands, which takes into account the interests of the wood-harvesting entrepreneur, the harvesting organisation, the machine operators, the forest owners, the chip consumer and the community.

Studies **I** and **II** lie within the classical area of time and productivity studies. Studies **III** and **IV** analyse the cost of forest fuel supply systems as a whole from stump to the CHP plant at stand and regional level by using e.g. time consumption models gained from studies **I** and **II**. Study **III** also identifies the bottlenecks and development potential of the mechanised harvesting systems. The decision hierarchy for choice the method for harvesting energy wood from young stands is formed on the basis of a comprehensive literature review and key results of Studies **I, II, III** and **IV**.

2 MATERIAL AND METHODS

2.1 Time studies (Study I & II)

In studies I & II the time study was carried out manually by means of the continuous timing method using a hand-held data recorder and the work phases were divided into main phases. Every work element was measured. If the observed work elements were performed simultaneously during the time studies, the time with the highest priority was recorded. In the harwarder study the priority order was cutting, loading and driving and in the forwarding study the order was loading and driving. The accuracy of the hand-held data recorder was 0.6 seconds (1 cmin). Driving distances during forwarding and logging were measured using a thread meter with an accuracy of one metre (1 m). The time studies were used to construct the time consumption functions for productivity and supply cost analysis.

Each of the harwarders' and forwarders' working cycles (clock time) was divided into effective working time (E_0h) and delay time (Haarlaa et al. 1984, Mäkelä 1986). The auxiliary time of each work main phase (e.g. work planning and preparation) was included in the effective working time. Delay times (e.g. breaks and machine service/repair) were measured but not included in the analysis, since the studies were too short to obtain an accurate estimate of a general delay time of harwarder and forwarder work and because a follow-up study was not carried out in the studies.

2.1.1 The time study of the forwarder based harwarder

The harwarder time study was carried out on 14 different time study plots (I). The time study plot was the strip where the harwarder harvested a full load of energy wood. The mean height of the removed whole trees varied from 8 to 12 metres, cutting removal varied from 800 to 4500 trees/ha, whole tree volume varied from 17 to 48 dm^3 and harvested volume per hectare varied between 24–95 m^3ha^{-1}. Trees were harvested with branches (whole-tree method) and the time study plots were dominated by either birch or pine. The nature and slope of the ground surface were normal (Tavoiteansioon perustuvat puutavaran…1990). The distance between strip roads was 20 metres on average and the width of the strip road was approximately 4 m. The base machine of the energy wood harwarder was an eight-wheeled Valmet 840 forwarder and a Moipu 400 E cutting-loading head was mounted on the harwarder crane, which had a reach of 10 m. In the study the operator-contractor had five months of practice in harwarder work and several years of working experience related to logging and earthmoving work. The time studies were carried out in natural light during the daytime from 23 to 27 September 2002 in Posio, in northwestern Finland (I).

The work cycle of a harwarder can roughly be divided into cutting and forwarding operations. The forwarder-based harwarder used a working method in which the machine firstly reversed into the stand and opened the strip road. The strip road was opened by cutting trees over the bunk. The removed trees were piled alongside the strip road and the driver estimated the length of the strip road so that there was enough wood for one load. After opening the strip road, on the way out of the stand, the harwarder thinned both sides of the opened strip road and loaded the processed trees onto the bunk (I). The lifting height of the harwarder crane was not sufficient to enable the lifting of the accumulated tree bunches straight onto the bunk. Hence, the accumulated bunches had to be laid on the ground before taking a new grip for loading (I). The new grip for loading was in the middle of the tree bunch. After cutting and loading, the fully loaded harwarder drove to the roadside storage site and started unloading. Following unloading the harwarder drove back to the stand and continued logging.

The volume of removals from the time study plot was estimated using the stump diameter (I). In each time study plot, sample plots with a radius of 3.99 metres were systematically set up. The stump diameters of the removed trees were measured by tree species at each sample plot. Breast height and height of removed trees (stumps) were derived by sample tree data and linear regression. The stem volume of harvested trees was calculated using the breast height diameter and height (Laasasenaho 1982). The volume of tree branches and needles was determined using the biomass models of Hakkila (1991) and the basic densities produced by Hakkila (1978). The volume of removal on the time study plots was the average volume removed from the sample plots. The harwarders' productivity (m^3 E_0h^{-1}) was calculated by dividing the volume of removal by the effective working time in the time study plot (I).

2.1.2 The time study of forwarding whole trees

The data collection procedure used in whole-tree forwarding consisted of a set of time studies. The time study data was comprised of 97 forwarder loads of which 46 loads were forwarded following motor-manual cutting and 51 loads were forwarded following mechanised cutting (II). Time studies were carried out using two Timberjack 810B forwarders and two operators. Both forwarder operators were motivated and experienced (20 and 2 years of working experience). In addition to the abovementioned energy wood forwarding experience, the operators had several years of work experience in other forest machine work.

Stand circumstances were comparable; the nature and slope of the ground surface were normal (flat) (Tavoiteansioon perustuvat puutavaran…1990) and similar for both cutting methods including the bearing capacity of the mineral soil (II). The time studies were carried out in natural light during the daytime, with lighting conditions being similar for both cutting methods. The distance between strip roads was 20 m on average, and the width of the strip road was approximately 4 m. The cutting removal from time study stands was frequently composed of broadleaf trees, mostly birch *(Betula pendula or pubescens*). Due to limited resources, it was not possible to survey the number and volume of removed and remaining trees, but the variation range of remaining trees after pre-commercial thinning was 1,000 to 1,500 trees per hectare in Finland; the time study stands were not an exception to that rule (II).

The time studies of forwarding, after motor-manual cutting, were carried out during the period from 10 to 23 October 2002 at Tohmajärvi (23°25'N, 62°16'E) in Eastern Finland (II). The forwarded energy trees were felled and bunched by professional forest workers. It was not possible to determine the load of each individually; therefore, an average and constant payload value was used. The average payload was determined when the forwarded trees were chipped at the roadside landing and delivered to the heating plant, where the delivered volumes were measured. The estimation of material losses during storing and after chipping was based on visual observations. According to the measurements, the average payload of motor-manually felled trees was 5.7 m^3.

Time studies of forwarding, after mechanised cutting, were carried out during the period from 7 to 17 April 2003 at Kannus (23°53'N, 63°53'E) in Western Finland (II). Trees at the study sites were felled and bunched by a Timberjack 720 accumulating felling head (formerly EnHar), which was attached to a Valmet 901 harvester. Bunches were not covered by snow; however, the ground snow cover at the time of forwarding was approximately 10 cm. The payload was estimated using a load scale, and the scale value was converted to solid cubic metres using a density factor of 850 kg m^{-3} fresh wood (Kaj Finne pers. comm.). The density factor was based on Biowatti Oy's follow-up studies and chipping tests. The payload of the trees felled using mechanised cutting varied between 5.5 and 8.2 m^3, with 6.2 m^3 being the average.

2.2 Regression analyses (Study I & II)

2.2.1 Data analysis of the harwarder time study

The time consumption of the work phases in the harwarder logging was formulated by applying a regression analysis in which the harvesting conditions (tree volume, harvesting intensity, forwarding distance, etc.) were independent variables (I). The SPSS statistical application was used to carry out a regression analysis to estimate logging productivity. The calculation unit for effective time (E_0h) consumption for each work element was seconds per m^3 (solid) or seconds per tree. The whole time consumption of the harwarder logging load cycle was calculated by summarising the time needed for each stage of the cutting and forwarding work.

The logging cycle of the forwarder based harwarder was divided into cutting and forwarding operations, and further into work elements. The determined productivity functions for the main working elements were: 1. Opening the strip road, 2. Felling and bunching, 3. Moving, 4. Loading, 5. Forwarding to the landing and driving back empty to the stand, 6. Unloading.

Cutting removal (trees per ha) and tree volume with branches (dm^3) were independent variables when modelling the time consumption of the strip road opening. The length of the strip road by load was dependent on the payload and the energy wood concentration per strip road. The most important productivity factors in multiple tree handling were tree volume and number of trees per accumulation. The number of trees per crane cycle was modelled by the cutting removal and the tree volume. Felling and bunching time per tree when using accumulation was calculated by the tree volume and number of trees per crane cycle. Time consumption of driving during cutting and loading was modelled by the number of trees removed. Moving time per tree decreased when the harvesting intensity of stems increased.

The grapple load was the main independent variable of the time consumption during loading. The larger the piles in the stand the easier and faster it was to grab larger grapple loads. The grapple load was calculated by the size of the cutting and loading point. The size of the cutting and loading point was determined by the energy wood concentration, m^3 per 100 m of strip road. The relationship between grapple load and size of cutting and loading point and also the relationship between the size of the cutting and loading point and energy wood concentration were assumed to be linear.

The time consumption models of driving unloaded and driving with a load were the same for both the harwarder and forwarder because it was noted that the driving speed of a forwarder-based harwarder does not differ from the driving speed of a normal forwarder (I, II). The grapple load was the independent variable for time consumption in unloading. The grapple load for unloading was almost double compared to the grapple load for loading. In the time studies the grapple load for unloading was 0.3 m^3 on average.

2.2.2 The data analysis of the forwarding time study

The recorded time study data and the measured data of stand and load characteristics were combined as a data matrix. The time consumption (E_0h) of each work phase in forwarding, following motor-manual and mechanised cutting, was formulated by applying a regression analysis (II). Different transformations and curve types were tested to ensure that the residuals of the regression models were as symmetrical as possible and to achieve the best values for the coefficients of determination for the final models. The regression analysis was carried out using the SPSS statistical package.

Those work phases in which the cutting method does not affect the time consumption were modelled by using the whole time study data. It was assumed that the time consumption of driving unloaded, driving with a load, and unloading were independent of cutting method. Time consumption for loading and driving during loading were individually modelled for motor-manual and mechanised cutting, since remarkable differences were noted in average grapple loads, sizes of loading points and driving distances between loading points between cutting methods.

Regression analysis of the variables with appropriate transformation was used for modelling the time consumption of the work phases. For example, time consumption of driving unloaded and driving with a load was explained by the forwarding distance. Energy wood concentration on the strip road (m^3 $100m^{-1}$) was derived from the driving distance during loading and the payload in the work cycle. The size of the loading point (m^3) was calculated by dividing the payload by the number of movements between loading locations in the work cycle. Grapple loads during the loading and the unloading work were based on average values per load. The final calculation unit for time consumption for every work element was second (s) per solid cubic metre (m^3).

2.3 Productivity and supply cost analysis (Study III & IV)

2.3.1 Production stages of the procurement system

The aim of studies III and IV was to compare and analyse the most common logging systems and supply chains of forest chips that are used in early thinnings in Finland by using existing productivity models and parameters at a stand or regional level (III, IV). The study comparisons of the alternative supply chains and the logging systems started with organising the procurement activities, continuing to logging, comminution and transportation, and finally to delivering the chips to the end user. The results were expressed as Euros per solid cubic metre (€ m^{-3}).

In study III the procurement chains were based on chipping at the roadside landing or at the terminal (Figure 1). The compared logging systems were: the motor-manual and the mechanised cutting of whole trees and forwarding by the forwarder and logging of whole trees by the harwarder (III). Whole trees were transported to the terminal using a biomass truck equipped with solid side panels and bottom. The chips from the roadside landing and from the terminal were transported using a standard chip truck. Chipping was done at the roadside landing and at the terminal by a truck-mounted drum chipper.

In study IV it was assumed that a conventional harvester-forwarder chain was used in logging operations. A normal harvester head, suitable for timber cutting, was equipped with accumulating accessories capable of multitree processing, and trees were recovered for energy purposes. Logged trees were chipped at the roadside landing directly into the load space of the truck-trailer unit. After chipping the fuel chips were transported to the plant. At the plant the chips were unloaded after weighing into the hopper of the delivery bay.

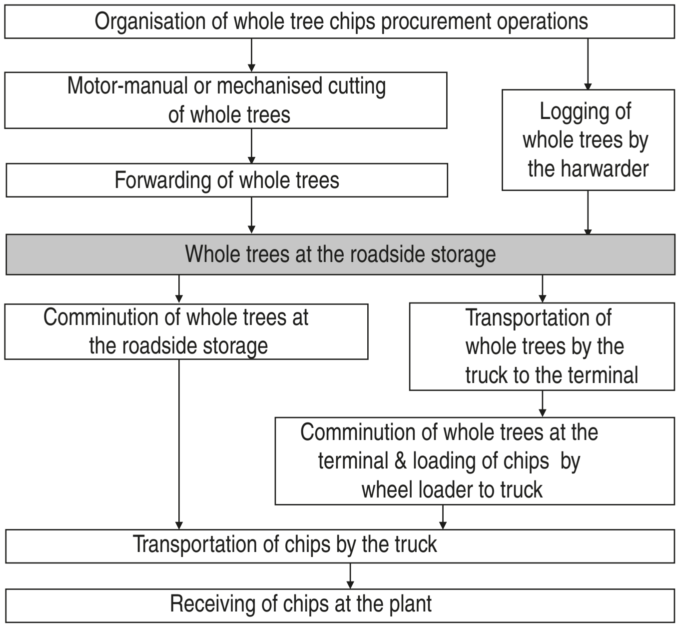

Figure 1. The logging systems and supply chains of study III by the main work stages.

2.3.2 Productivity parameters of the procurement system

In study III the cost of the motor-manual cutting of whole trees was based on a collective labour agreement (Metsäalan palkkaus 2006) and productivity models for the felling-bunching of whole trees (Vastamäki and Örn 1995) with a chainsaw and felling frame. In the mechanised cutting, productivity was based on a time consumption model for a medium size thinning harvester equipped with a simple accumulating felling head that is only designed to fell and bunch trees and is not capable of feeding and delimbing tree bundles (Laitila et al. 2004). In the harwarder system, productivity was calculated for the harwarder based on a conventional medium-size forwarder (I).

The harvester's effective time (E_0) productivity was converted to gross effective time productivity (E_{15}), which included delays shorter than 15 min, using the coefficient 1.3. The gross effective time coefficient of the harwarder was 1.25. In studies III and IV the operating hour productivity coefficients for logging machines were based on the author's estimates, as follow-up study data from pre-commercial thinnings was not available and the data from the roundwood harvesting was considered invalid for this study (e.g. Kärhä 2001).

In study IV the productivity of cutting whole trees and multi-stem delimbed shortwood using the multi-tree processing technique was based on the study of Heikkilä et al. (2005) and the productivity model is published in the Excel-based "Cost calculator for delimbed energy wood" cost calculation program (Laitila 2006). With small trees the relative productivity difference is the largest since the proportion of crown biomass of the total tree volume is bigger than with larger trees. The harvester's effective time (E_0) productivity was converted to gross effective time productivity (E_{15}), which included delays shorter than 15 min, using the coefficient 1.3 (III).

The productivity of forwarding whole trees after mechanised and motor-manual cutting was calculated according to the models of Laitila et al. (2007) in studies III and IV. In study IV the forwarding productivity of multi-stem delimbed shortwood was calculated by the time consumption models for forwarding long pulpwood (3–5 metres) in thinning conditions (Kuitto et al. 1994). The payload of the medium-sized forwarder was estimated to be 6.0 m³ for whole trees and 9.0 m³ for multi-stem delimbed shortwood (solid). The forwarder's effective time (E_0) productivity was converted to gross effective time productivity (E_{15}) using the coefficient 1.2 (III).

The chipping was done by a truck-mounted drum chipper in studies III and IV. The chipper's productivity at the roadside storage was estimated to be 34 m³ (85 loose-m³) per operating hour (E_{15}) for both whole trees and multi-stem delimbed shortwood (III, IV). At the terminal the chipping productivity was 44 m³ E_{15}^{-1} (III).

The chips were transported by a truck-trailer unit with a payload of 44 m³ (III, IV). When transporting whole trees the payload was estimated to be 25 m³ (III). The truck transportation time consisted of: driving with an empty load, driving with a load and terminal time. The terminal time included loading, unloading, waiting and auxiliary time. The time consumption of driving, with and without a load, was calculated as a function of transportation distance according to the speed functions for chip trucks (Ranta 2002). The trucks were assumed to drive to the destination fully loaded and return to the starting point empty; the same transporting distance was used for driving both with and without a load. In the supply chain, which was based on chipping at the terminal, the extra transportation distance for the chips from the terminal to the end-use facility was 10 km (III).

The loading time of the chip truck-trailer unit was 1.29 hours at the roadside landing, which contained both the direct and indirect chipping time. At the terminal the loading time of chips was 0.37 hours and the work was done using a wheel loader (III). The loading time of the truck-trailer unit was estimated to be 1.0 hour when transporting whole trees from the roadside storage to the terminal (III). The unloading time of whole trees with a crane was estimated to be 0.8 hours, which also included the auxiliary and waiting time at the terminal. The unloading time of chips at the end-use facility was estimated to be 0.8 hours, which also included the auxiliary and waiting time (III, IV).

2.3.3 The operating cost calculations

The operating costs (excluding VAT) of the logging machines, chipper and truck-trailer unit were calculated per gross effective hour (E_{15}) using the common machine cost calculation method (e.g. Harstela 1993) and costs were presented in Euros (€). The costs included both time-dependent costs (e.g. capital depreciation, interest expenses, labour costs, insurance fees and administration expenses) and variable operating expenses (e.g. fuel, repairs, service and machine transfers). In addition to the annual total cost, 5% was added to take into account the risk of entrepreneurship. Capital costs were calculated by the annuity method, using an interest rate of 6% and salvage value of 40% for logging machines and transport vehicles. The lifespan of the logging machines and transport vehicles was standardised to 12 000 operating hours (E_{15}) and the annual working time was standardised to 2 600 operating hours (III, IV).

The calculation values for labour costs, fuel, insurance fees, repairs and service expenses were obtained from Koneyrittäjien Liitto ry (The Trade Association of Finnish Forestry and Earth Moving Contractors) and Metsäalan Kuljetusyrittäjät ry (Association of Forest Industry Road Carriers). Average prices of machines and transport vehicles were obtained from the manufacturers.

The utilisation degrees of logging machines were obtained from the study of industrial roundwood harvesting (Kärhä et al. 2007) and the chipper's utilisation degrees at the terminal or in roadside use were derived from the study of Ikäheimo and Asikainen (1998). The utilisation degree of the transport vehicles was obtained from the average time consumption of timber trucking in Finland (Nurminen and Heinonen 2007) while the utilisation degree parameter was set as the same for both truck-trailer types.

For truck transportation the hourly cost was divided between driving and terminal times. In the calculation, the annual driving kilometres of the truck-trailer unit was 90 000 km. When calculating the terminal time cost of the truck-trailer unit, the fuel, oil and service costs were excluded from the total costs.

The unit costs (€ m^{-3}) of the working phases were calculated by dividing the hourly cost by productivity. The overhead costs of the procurement operations were estimated to correspond to the average organisation costs of industrial roundwood in Finland (Kariniemi 2006 and 2008). The same organisation cost was set for both whole trees and multi-stem delimbed shortwood as well as for all logging systems and supply chains in studies III and IV. The stumpage price for the harvested raw material was not considered while the transferring costs of machines between sites were included in the operating hourly costs of the machines.

2.4 Procurement cost and availability analysis (Study IV)

The aim of study IV was to estimate and compare the harvesting and procurement costs of whole-tree and multi-stem delimbed shortwood chip production. Furthermore, available volumes and procurement costs of small-diameter tree chips were estimated within a 100-kilometre radius from a hypothetical combined heat and power plant located in Jyväskylä in Central Finland, when using different stand selection criteria and cutting methods. The analyses were performed as simulated treatments in young stands based on existing productivity and cost functions and yield calculations concerning the sample plots of the 9th National Forest Inventory of Finland. It was assumed that all the small-diameter wood chips from the potential procurement area were freely available without the prior sorting of different companies or ownership structure (IV).

2.4.1 Forest data

The available volumes of forest chips from young forests around the city of Jyväskylä were based on sample plot data from the 9th Finnish National Forest Inventory (NFI 9) from the forestry centres of Etelä-Pohjanmaa, Etelä-Savo, Häme-Uusimaa, Keski-Suomi, Pirkanmaa and Pohjois-Savo (Tomppo et al. 1998a, Tomppo et al. 1999, Korhonen et al. 2000a, b, Tomppo et al. 2001). Satellite images and other auxiliary data were used to downscale the data from forestry centre level to municipality level (Tomppo et al. 1998b). Calculations of forest chip resources were made for the sapling stands (dominant height >1.3 m, diameter at breast height (dbh) <8–10 cm) and young thinning stands (dominant height usually >7 m, dbh 8–16 cm) needing thinning within the first five-year period. The maximum transportation distance was 100 kilometres along the existing road network (Ranta 2002).

The area that a NFI sample plot represents in a certain municipality and stand development class was calculated as follows (Laitila et al. 2004, Ranta et al. 2007):

$$N_{khl,\,y} = \frac{\frac{a_{khl}}{A_{khl}} \times A_{khl,\,y}}{n_{khl}} \qquad (1)$$

where a_{khl} was the area estimate for improvement fellings according to the NFI in the development class *khl* in the forestry centre, A_{khl} was the estimate of total area for development class *khl* according to the NFI in the forestry centre, $A_{khl,y}$ was the area estimate for development class *khl* in municipality y according to multi-source NFI data and n_{khl} was the number of sample plots needing thinning in the forestry centre. The volume of harvested biomass in the calculated area unit, $N_{khl,y}$, was obtained by multiplying the area with the biomass yield per hectare in the sample plot. Harvesting volume for the five-year period was converted to annual harvesting volume simply by dividing it by five.

2.4.2 Computation of the harvesting intensity

The removal of multi-stem delimbed shortwood was calculated for each sample plot by simulating the tending of a young stand or thinning according to silvicultural guidelines (Luonnonläheinen metsänhoito – Metsänhoitosuositukset, 1994). In the simulation, trees tallied to the plot were first sorted by diameter. Starting from the smallest tree, trees were harvested until the basal area of the remaining trees reached the recommended basal area after thinning. The volume of the removed stems was then totalled. Trees with a dbh of more than 9.5 cm were classified as industrial roundwood, while those with a dbh of less than 9.5 cm and more than 4 cm were classified as energy wood. Trees with a dbh less than 4 cm were not included in the total energy wood volume. The roundwood assortment had to fulfil the common quality requirements for pulpwood (birch, pine or spruce, minimum top diameter 6 cm and the length of the bolt >2 m). In the total volume, trees were not classified as industrial roundwood or pure energy wood because all trees were harvested for energy using either the whole-tree or multi-stem delimbed shortwood method if the below-mentioned stand selection criteria were fulfilled. In the calculation, the degree of recovery of biomass in the harvesting operations was assumed to be 100%.

When using the whole-tree method, the crown mass was added to the total stemwood volume using crown mass factors (Hakkila 1991). The dry mass was then further converted to volume using dry mass density factors (Hakkila 1978). The crown mass included living branches and needles. Dead branches were excluded, as they were assumed to be lost during the harvesting.

In multi-stem delimbed shortwood harvesting, the allowed lengths of the bundle of delimbed and bucked stems were both 3 metres and 5 metres while the minimum top diameter was 4 cm. In the case of trees that had a usable stem part longer than 3 metres but shorter than 5 metres the cross cutting was done at the 4 cm top diameter point. The length of the base bolt was thus exceptionally allowed to vary between 3–5 metres.

The bucking and bolt volume of the multi-stem delimbed shortwood was calculated as a function of tree species as well as the average height and dbh of trees at the NFI sample plot. The bucking simulation and volume calculation for the NFI sample plots were done by the Excel-based RUTILA program (Pasanen 2004, Heikkilä et al. 2005). With RUTILA, the calculation was based on the taper curve models of Laasasenaho (1982).

2.4.3 Transporting distances and stand selection criteria

The calculation of transporting distances via the existing road network to Jyväskylä was based on GIS analysis and databases of forestry companies from the year 2000 (Asikainen et al. 2001, Ranta 2002). The transporting distance from municipality x to Jyväskylä was the average transporting distance from the logging stands of municipality x. The average transporting distances varied between 12 and 100 kilometres. For the procurement cost calculation the average forwarding distance in each municipality was also calculated. The calculations were also based on databases of logging stands of forestry companies from the year 2000 (Asikainen et al. 2001, Ranta 2002). The forwarding distances varied between 181 and 301 metres, with the average being 232 metres.

The NFI sample plot data contained information on, for example, soil type (mineral or peat soil), habitat type, dominant species and average diameter and height of the trees. Furthermore, the cutting removals of industrial roundwood, whole trees and multi-stem delimbed shortwood per hectare were calculated in the way presented earlier in this thesis. For the final summing of yield potential, different stand / sample plot selection criteria were applied (IV). These criteria were:

1) The maximum allowable removal of industrial roundwood was 25 m^3 (solid) per hectare and the minimum accrual of the energy fraction (whole trees or multi-stem delimbed shortwood) was 25 m^3 (solid) per hectare.

2) Trees were harvested, delimbed, from peat soil stands, spruce-dominant stands and mineral soil stands with a Vaccinum-type or poorer habitat.

3) Whole-tree harvesting was applied in mineral soil stands with a Myrtillus-type or more fertile habitat, excluding spruce-dominant stands.

3 RESULTS

3.1 Logging productivity of the harwarder

Felling and bunching represented 45% of the energy wood harwarder's effective working time in a stand where the forwarding distance was 250 m, the average volume of removed trees 25 dm³ and harvesting intensity 50 m³ ha^{-1} (Figure 2). Payload was 6.2 m³ on average. Opening strip roads took 18% of the total time consumption and loading of felled trees 17%. Time consumption of forwarding was 6% with a load and 5% with an empty load. Moving during cutting and loading and unloading at the landing both represented 5% of the effective working time (I).

The logging productivity of small trees with the harwarder method was 3.3 m³ E_0h^{-1} (effective working hour), when the tree volume was 25 dm³, harvesting intensity 50 m³ ha^{-1}, payload 6.2 m³ and forwarding distance 250 m (Figure 3). The tree size of the removals has the greatest effect on harwarder logging productivity. The increase of tree size from 10 dm³ to 50 dm³ increased harwarder logging effective hour productivity from 2.2 m³ E_0h^{-1} to 3.7 m³ E_0h^{-1}. The lengthening in the forwarding distance from 50 m to 500 m decreased logging productivity by 0.6 m³ per effective working hour. The increase in the harvesting intensity from 25 m³ha^{-1} to 75 m³ha^{-1} improved the productivity of harwarder logging by 0.5 m³ per effective working hour (I).

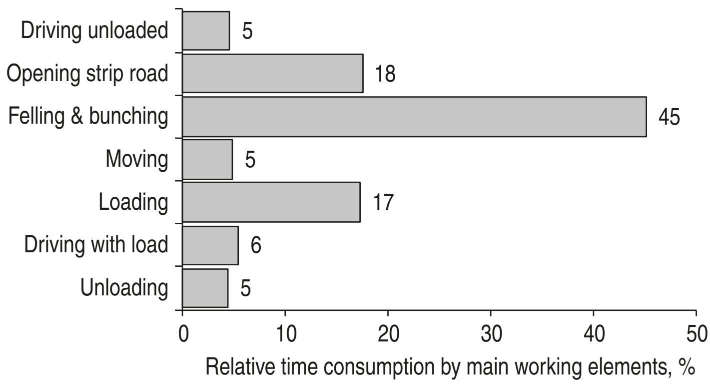

Figure 2. Main elements of the energy wood harwarder's effective working time (I).

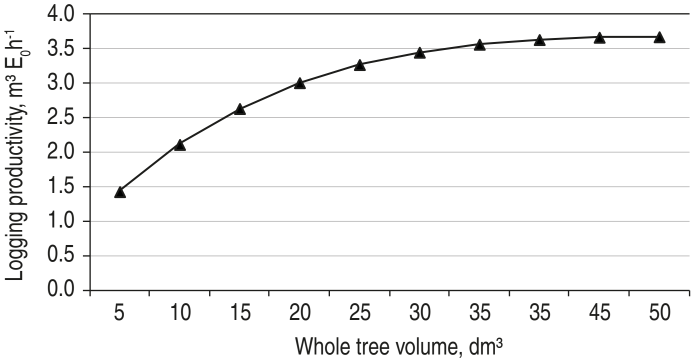

Figure 3. The effective hour productivity of energy wood logging with a harwarder as a function of tree volume. Forwarding distance 250 m and harvesting intensity 50 m³ ha^{-1} (I).

3.2 Productivity of forwarding whole trees

Figure 4 illustrates the absolute effective working time consumption by load and main working elements when the forwarding distance was 250 m, payload was 6 m^3 and harvesting intensity was 60 m^3ha^{-1} (II). For assessing the time consumption, driving with a load, driving with an empty load and unloading were set as constant for both cutting alternatives. Figure 4 shows that mechanised cutting clearly enables faster loading, and the absolute time benefit per load is 20 minutes and 9 seconds in effective working time.

This significant productivity difference was explained by the fact that in mechanised cutting the removed whole trees are bunched into large piles close to the side of the strip road, which enables the driver to load full or almost full grapple loads from the well-arranged piles (II). This clearly improves the output of loading work and thereby helps to reduce forwarding costs. After motor-manual cutting, the piles of wood are small and scattered over a larger area. Therefore the operator has to pick up one bunch of wood, paying attention to the standing trees, then reposition the bunch on top of another pile, re-grapple both bunches and place the grapple load either on the bunk of the forwarder or on top of the next pile of wood (II). This multiple-pile loading, far from the strip road, significantly decreases loading productivity.

Figures 5 and 6 show the sensitivity analysis of forwarding productivity after motor-manual and mechanised cutting according to forwarding distance, payload and harvesting intensity. The output in forwarding following mechanised cutting increased by 1.7 m^3 per effective hour when the payload grew from 4 to 9 m^3 and forwarding distance was set at 50 m (Fig. 5). When the forwarding distance was 450 m, output in forwarding improved by 3.9 m^3 per effective hour due to the increase in payload from 4 to 9 m^3. Corresponding values for forwarding productivity after motor-manual cutting were 0.4 and 1.7 m^3 per effective hour, respectively. The payload is more important when cutting is mechanised since the relative time consumption of driving with or without a load is greater compared to relative time consumption after motor-manual cutting (Fig. 4). In Figure 5 harvesting intensity was set at 60 m^3ha^{-1}.

The increase in harvesting intensity from 30 m^3 ha^{-1} to 75 m^3 ha^{-1} improved forwarding productivity by 5 m^3 per effective working hour when the forwarding distance was 50 m and cutting was mechanised (Fig. 6). When the forwarding distance was 450 m, the increase in

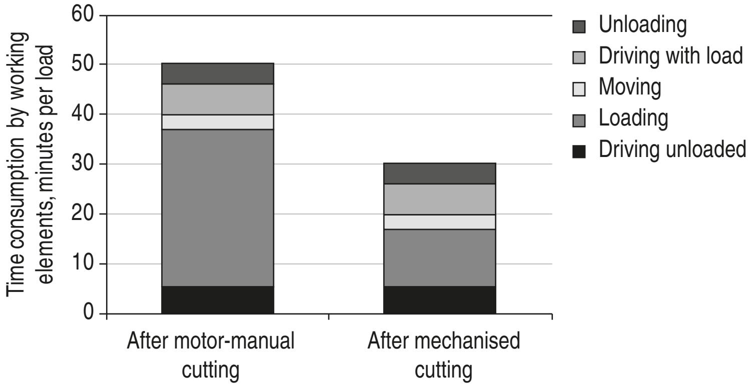

Figure 4. Absolute time consumption by main working elements, when forwarding whole trees after motor-manual and mechanised cutting. Forwarding distance is 250 m, payload 6 m^3 and harvesting intensity of energy wood 60 m^3ha^{-1} (II).

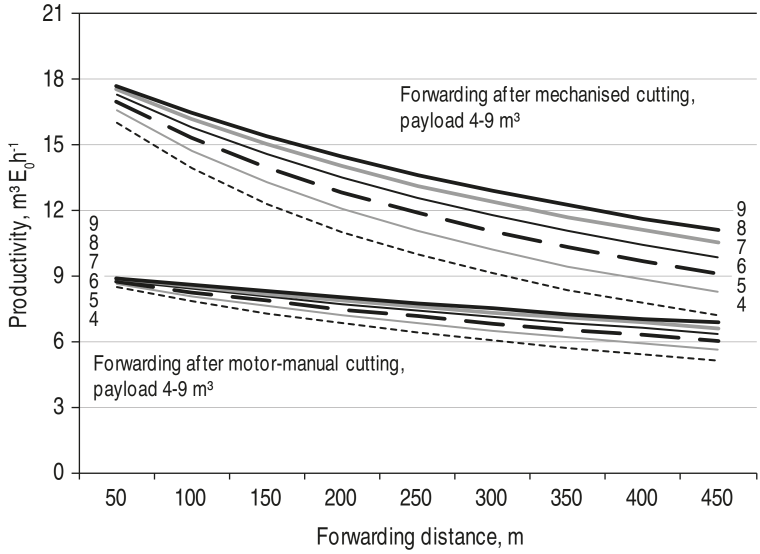

Figure 5. Forwarding productivity after motor-manual and mechanised cutting according to payload and forwarding distance. The harvesting intensity is 60 m^3ha^{-1} (II).

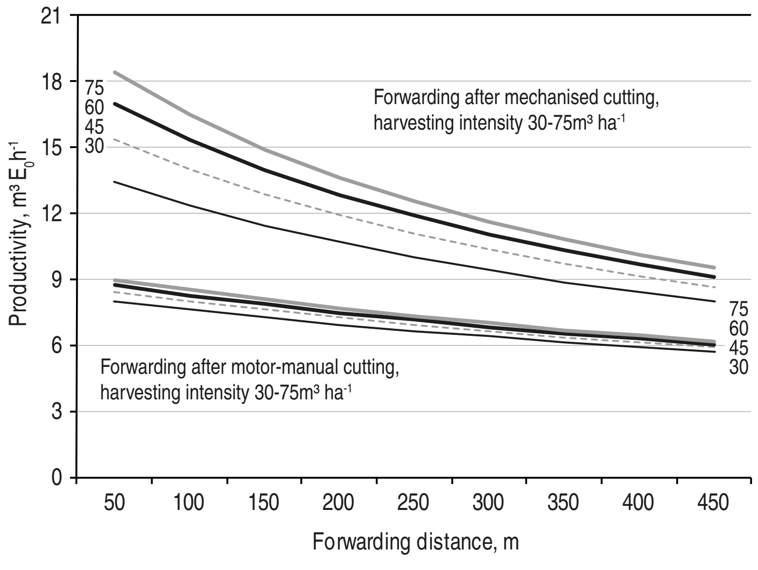

Figure 6. Forwarding productivity after motor-manual and mechanised cutting according to harvesting intensity and forwarding distance. The payload is 6 m^3 (II).

the harvesting intensity improved forwarding productivity by 1.5 m^3 per effective working hour. After motor-manual cutting of whole trees, a clear increase was shown in the harvesting intensity, from 30 m^3 ha^{-1} to 75 m^3 ha^{-1}, while forwarding productivity improved at the 50 m forwarding distance by 1 m^3, and at the 450 m forwarding distance by 0.5 m^3 per effective hour (Fig. 6). Harvesting intensity has a moderate effect on forwarding productivity after motor-manual cutting. This can be explained by the fact that although the yield increases, the forwarder must collect trees from smaller bunches and some of the trees are far from the strip road. In mechanised cutting, however, the increase in harvesting intensity results in bigger bunches, which speeds up loading (II).

3.3 Supply cost and logging productivity analysis

3.3.1 The procurement costs of whole-tree chips

The procurement cost of whole-tree chips varied between 31.9 and 41.6 € m^{-3} at the end-use facility depending on the logging system and supply chain used (Figure 7). The logging system based on a harvester with an accumulating felling head was the cheapest while the harwarder system was the most expensive (III). The logging cost at the roadside storage point was 19.1 € m^{-3} for the two-machine system, 22.6 € m^{-3} for the system based on motor-manual cutting and 23.0 € m^{-3} for the harwarder system. The supply chain based on comminution at the roadside landing was found to be significantly cheaper than comminution at the terminal. The cost difference between supply chains was 5.7 € m^{-3}. The overall cost of chipping, handling and transporting totalled 9.2–15.0 € m^{-3} depending on the supply chain used for the production of whole-tree chips. The lower comminution cost at the terminal was not enough to cover the higher cost of transporting unprocessed material to the terminal, the handling cost of chips at the terminal or the delivery cost to the end-use facility.

Cutting was the most expensive work stage in the procurement of whole-tree chips (12.9–13.5 € m^{-3}) (Figure 7). The cost difference in cutting between motor-manual and mechanised cutting was small; nevertheless, motor-manual cutting was 0.6 € m^{-3} cheaper compared to the mechanised cutting of whole trees when the tree volume was 30 litres (Figure 7). Whereas in forwarding, the cost of motor-manual felled trees (9.6 € m^{-3}) was almost double that of mechanised felled trees (5.6 € m^{-3}). Also in the fully-mechanised logging of whole trees, the cost difference between two-machine and harwarder-based logging systems was significant, 3.9 € m^{-3} (Figure 7).

Figure 8 presents a sensitivity analysis of logging costs as a function of whole tree volume, when the logging is based on motor-manual or mechanised cutting or work is done by the harwarder. In the cost comparison the tree volume varied between 10–50 litres, whereas the forwarding distance (200 m) and the removal (60 m^3 ha^{-1}) were constant. The breakeven point for the logging cost of the motor-manual-worker-forwarder system and the harvester-forwarder system was when the tree volume was about 14 litres (Figure 8). For larger tree volumes the logging costs of the harvester-forwarder system were significantly lower than the

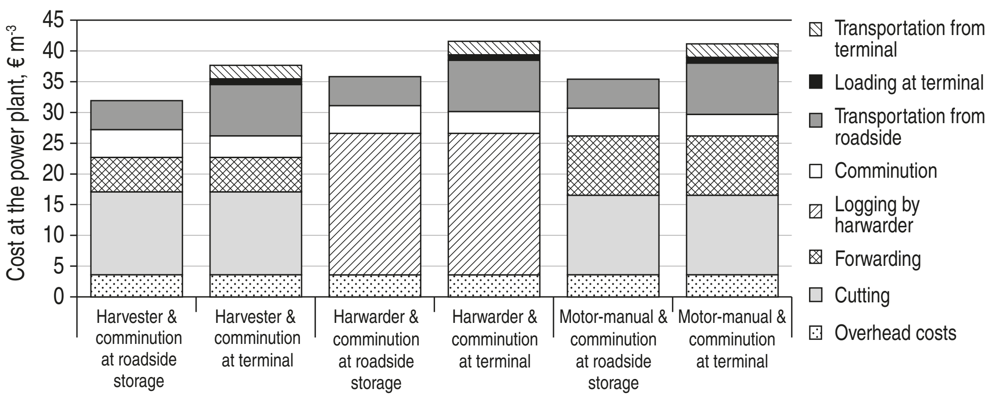

Figure 7. Cost of whole-tree chips by main work stages at the power plant, € m^{-3} (III). The forwarding distance was 200 m, harvesting intensity 60 m^3ha^{-1}, the volume of the whole trees 30 litres and transporting distance 40 km.

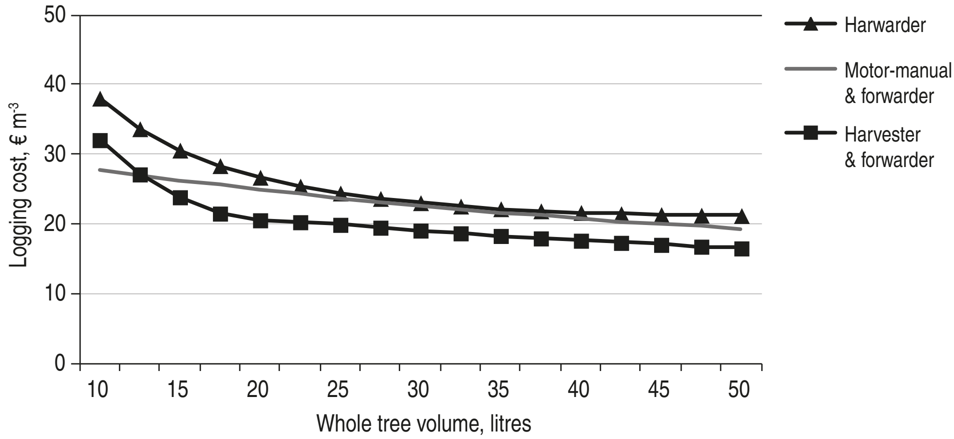

Figure 8. Logging cost (€ m^{-3}), when the harvesting intensity was 60 m^3 ha^{-1}, the tree volume 10–50 litres and the forwarding distance 200 metres (III).

logging costs of the motor-manual-worker-forwarder system. The logging costs of the motor-manual worker-forwarder system were lower for all tree volumes than the logging costs for the harwarder (Figure 8). However, when the tree volume was larger than 23 litres, the logging costs of the motor-manual worker-system and the harwarder systems were almost equal (III).

3.3.2 The analysis of logging productivity

Figures 9 and 10 explain the noted differences based on productivity equations for the forwarding and mechanised cutting of whole trees (Laitila et al. 2004, I, II). Table 1 details the size of the loading point and grapple load (m^3), when forwarding mechanically or motor-manually felled whole trees by forwarder or by the harwarder system, as well as the time consumption for the loading work (s m^{-3}). Table 2 presents the productivity parameters of the mechanised cutting by both harvester and harwarder, when the removal of whole trees amounted to 60 m^3 ha^{-1} and 2000 trees ha^{-1} and the volume of removed trees was 30 litres (III).

In the harwarder system the moving times of cutting and forwarding overlap and therefore the division of moving times between forwarding and cutting was difficult to determine. In this productivity analysis, the moving time, that is, when the harwarder thins the sides of the strip road and loads the removed trees onto the load space, focused on the forwarding work. Correspondingly, the time spent opening the strip road, which included both the opening of the strip road and moving on it, focused on cutting and especially on the work phase of driving during cutting (Table 2).

The harwarder's forwarding productivity was 2.9 m^3 E_0h^{-1} lower compared to the forwarder's productivity after mechanised cutting and 2.4 m^3 E_0h^{-1} higher compared to productivity after motor-manual cutting, when the forwarding distance was 200 m (Figure 9). For the harwarder system (Table 1), the size of the loading point was only 51% of the size of the loading point after mechanised cutting and 82% of the size after motor-manual cutting in similar stand conditions. The grapple load in the loading work was, on average, 0.17 m^3 for the harwarder and 0.22 m^3 for the forwarder after mechanised cutting. After motor-manual cutting the average grapple load was 0.10 m^3 (Table 1).

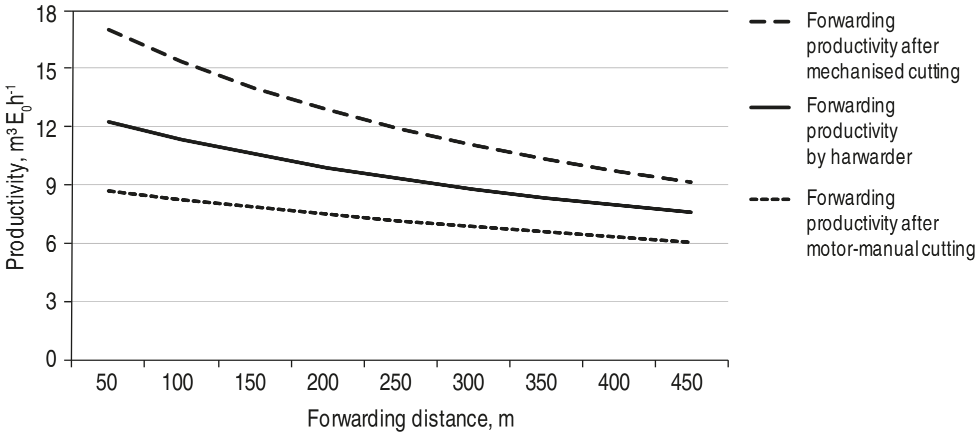

Figure 9. Productivity (E_0h) of forwarding as a function of forwarding distance after mechanised and motor-manual cutting and by harwarder system. The harvesting intensity of whole trees was 60 m^3 ha^{-1} (III).

The average grapple load means that, for example, when using the harwarder system, it takes six cycles (grabbing the tree bunches and lifting them onto the bunk) before one solid cubic metre of wood has been loaded. After mechanised cutting the forwarder operator has to repeat the loading cycle 4.5 times and after motor-manual cutting 10 times to load one solid cubic metre of wood in comparable stand conditions. Time consumption of the loading work by the harwarder was 174 s m^{-3}, while for the forwarder it was 115 s m^{-3} after mechanised cutting according to the productivity equations (Table 1). After motor-manual cutting the time consumption for the loading work was as high as 316 s m^{-3}. The average duration of the loading work cycle was 29 seconds for the harwarder. For the forwarder the crane cycle during loading took, on average, 25.6 seconds after mechanised cutting and 31.6 seconds after motor-manual cutting (Table 1).

Table 1. Productivity parameters of forwarding work according to logging system in similar stand conditions. The harvesting intensity of whole trees was 60 m^3 ha^{-1} at the stand.

	Forwarding after mechanised cutting	**Forwarding after motor-manual cutting**	**Harwarder system**
Size of loading point	0.55 m^3	0.34 m^3	0.28 m^3
Grapple load in loading	0.22 m^3	0.10 m^3	0.17 m^3
Time consumption of loading	115 s m^{-3}	316 s m^{-3}	174 s m^{-3}
Duration of crane cycle in loading	25.6 s	31.6 s	29.0 s
Driving during loading	28 s m^{-3}	28 s m^{-3}	46 s m^{-3}
Grapple load in unloading	0.6 m^3	0.6 m^3	0.3 m^3
Time consumption of unloading	43 s m^{-3}	43 s m^{-3}	50 s m^{-3}
Driving with load	50.4 s m^{-3}	50.4 s m^{-3}	50.4 s m^{-3}
Driving unloaded	43.2 s m^{-3}	43.2 s m^{-3}	43.2 s m^{-3}

The driving time of the forwarder between loading locations was the same, 28 s m^{-3}, for both cutting methods (Table 1), as the driving distances between the loading points were just a few metres per step (II). The harwarder's driving time between loading points was 46 s m^{-3}, which was almost double that of the forwarder. This is explained by the fact that the movements of the harwarder during cutting and loading were primarily dependent on the thinning work.

With the forwarder, the average grapple load in unloading was 0.6 m^3 whilst the harwarder's was just half of that (Table 1). The explanation for this significant difference is the structure of the harwarder's grapple. It is designed for both cutting and loading and thus the compromise grapple is not as efficient as the purpose-built timber grapple. In the unloading work the differences were not so large. For the forwarder the unloading took 43 s m^{-3} while for the harwarder the unloading productivity at the roadside landing was just 16% slower (Table 1). Obviously the movement speed of the harwarder crane had been adjusted to be faster compared to the movement speed of the forwarder crane in unloading.

In the mechanised cutting of thinning wood, the harvester's productivity was 1.1 m^3 E_0h^{-1} higher compared to the harwarder's productivity in thinning (Figure 10), when the tree volume

Table 2. Productivity parameters of mechanised cutting work in thinnings depending on the logging system when the harvesting intensity of whole trees was 60 m^3 ha^{-1} and tree volume was 30 litres.

	Harvester & accumulating felling head	Harwarder system
Time consumption of cutting	476 s m^{-3}	441 s m^{-3}
Driving during cutting	49 s m^{-3}	184 s m^{-3}
Total	525 s m^{-3}	625 s m^{-3}

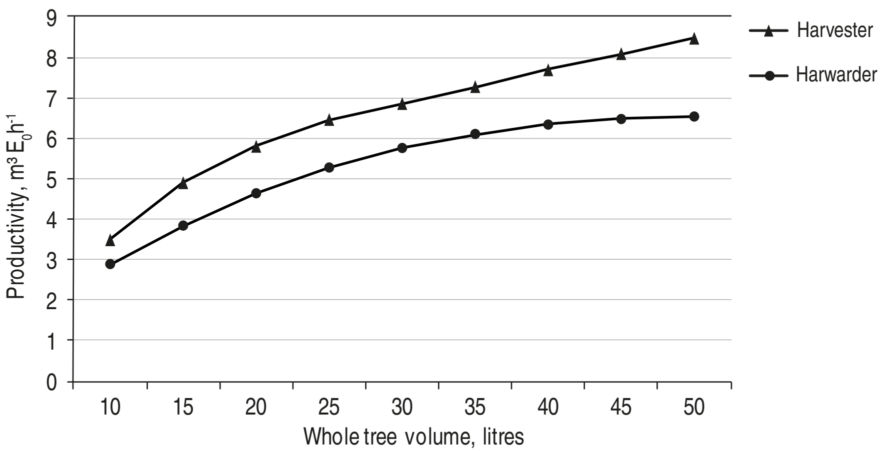

Figure 10. Productivity (E_0h) of mechanised cutting as a function of tree volume by energy wood harvester and harwarder. Harvesting intensity of whole trees was 60 m^3 ha^{-1} and the number of harvested trees 6000–1200 trees ha^{-1} (III).

was 30 litres and removal was 60 m³ and 2000 trees per hectare. Time consumption of cutting of whole trees was 476 s m^{-3} for the harvester and 441s m^{-3} for the harwarder (Table 2), which actually corresponds to the cutting time when thinning the sides of the strip road. The driving time consumption during cutting was 49 s m^{-3} for the harvester while for the harwarder the moving time was more than three times longer (Table 2). In the harwarder system the moving time on the strip road was as high as 184 s m^{-3}. The forwarder-based harwarder is quite slow at opening the strip road, as it has to operate the crane over the bunk (I). This means that the crane's reach in the driving direction is very short and the extent to which the machine can be used to open up the strip road for itself is small. In the study of Laitila and Asikainen (2006) strip road opening accounted for almost 18% of the total effective logging time (I).

3.3.3 The sensitivity analysis of logging

Figure 11 summarises the logging time consumption per operating hour and solid volume when harvesting whole trees using the two-machine system or the harwarder (III). The logging time consumption of the two-machine system was 0.28 operating hour per whole tree m³, of which the forwarding accounted for 0.09 $E_{15}h$ m^{-3} and cutting by the harvester 0.19 $E_{15}h$ m^{-3} (Figure 11). The logging time consumption of the harwarder was 0.34 $E_{15}h$ m^{-3}. The difference in the logging time consumption per m³, 0.06 $E_{15}h$ m^{-3}, is explained by the productivity elements, which are detailed in Figures 9 and 10 and Tables 1 and 2. Also the operating hour productivity coefficients (1.25, 1.20 or 1.30) that were used in the assessment of logging machines naturally made a significant difference. The combined productivity of the two-machine system per operating hour ($E_{15}h$) was 3.5 m³ and the corresponding productivity of the harwarder was 2.9 m³.

If a sensitivity analysis is conducted, in which it is assumed that the mechanised logging systems' operating hour productivity will remain constant (Figure 11), the hourly cost of the harwarder should decrease to 55.5 € h^{-1} in order to reach the same logging cost as when using the two-machine system. Correspondingly the hourly cost of the forwarder should

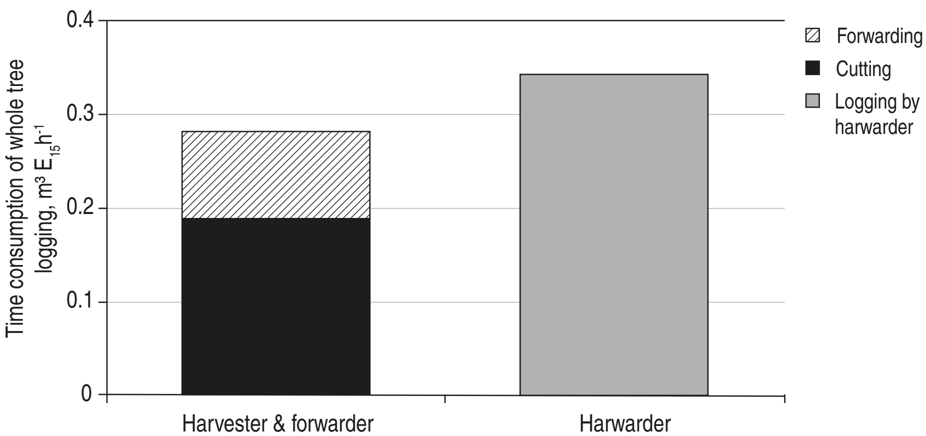

Figure 11. Logging time ($E_{15}h$) consumption per solid whole-tree cubic metre (m³) with the two-machine system and the harwarder when the harvesting intensity was 60 m³ ha^{-1}, tree volume 30 litres and forwarding distance 200 metres (III).

increase to 102 € h^{-1} and the harvester's to 92 € h^{-1} before it will reach the logging cost of the harwarder system (Figure 11). If it is supposed that the hourly costs of the logging machines remain constant, the operating time consumption per m³ of harwarder logging should decrease to 0.285 $E_{15}h$ m^{-3} in order to reach the same costs as using the two-machine system. Time consumption of 0.285 $E_{15}h$ m^{-3} is equal to productivity of 3.5 m³ $E_{15}h^{-1}$, which means that productivity should increase by 0.6 m³ $E_{15}h^{-1}$ or 20% from the current productivity level (III).

3.4 Available volumes and procurement costs of thinning wood for fuel in Central Finland

3.4.1 Logging costs of whole trees and multi-stem delimbed shortwood

In the sensitivity analysis of logging cost as a function of diameter, the logging costs of multi-stem delimbed pine shortwood were 14–76 € m^{-3} (Figure 12). Cutting costs were 9.8–69.3 € m^{-3} and forwarding costs 4–6.3 € m^{-3} (Figure 12). The logging costs of pine whole trees were 12.4–53.1 € m^{-3}. Of that the cutting costs were 7.8–45.3 € m^{-3} and forwarding costs 4.6–7.9 € m^{-3} (Figure 12). In the example sensitivity analysis presented in Figure 12, the harvesting intensity was 1500 stems per hectare, forwarding distance was 230 metres, dbh 6–13 cm and height of the pines 5.5–11.8 metres (IV).

3.4.2 Available volumes of whole trees and multi-stem delimbed shortwood

The availability analysis attested that delimbing lowered the cutting removal by 42% compared to whole-tree harvesting, when the minimum concentration for the fuel fraction at the sample plot was set at 25 m³ ha^{-1} (IV). Delimbing decreases the recovery rate at the site and as a result the potential volume recovered from the site becomes too small. Around the city of Jyväskylä, the available volumes of whole trees amounted to 467 000 m³ (solid) per year and delimbing decreased the available volumes of fuel fraction to 272 000 m³ per year (Figure 13). When the whole-tree harvesting method was limited to fertile mineral soil stands, excluding spruce-

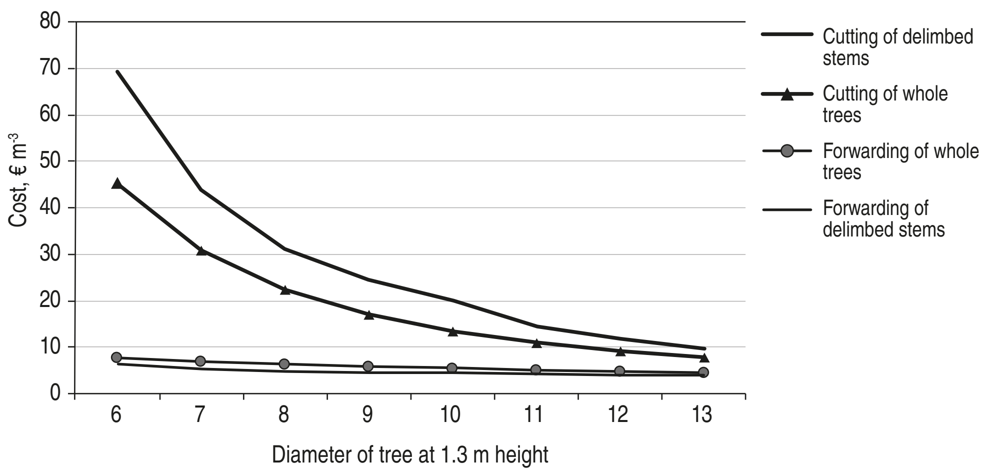

Figure 12. The cutting and forwarding costs of multi-stem delimbed pine shortwood and pine whole trees (IV).

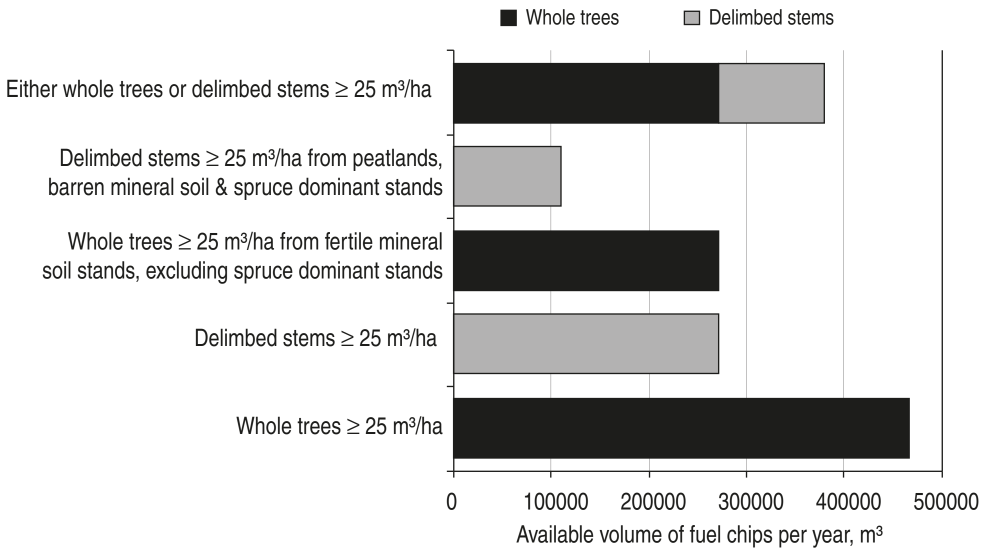

Figure 13. The available volumes of energy wood around the city of Jyväskylä when using different stand selection criteria and alternative cutting methods. Maximum transportation distance was 100 km (IV).

dominant stands, the available volumes of fuel fraction totalled 271 000 m³ per year. When harvesting delimbed fuel wood from peatlands, unfertile mineral soil stands (poorer than Myrtillus-type) and spruce-dominant stands, the annual available volumes totalled 110 000 m³ per year. Thus the maximum available volumes of fuel fraction from young thinning stands totalled 381 000 m³ per year (271 000 m³ whole trees + 110 000 m³ multi-stem delimbed shortwood) in Jyväskylä, when logging was carried out according to the current harvesting recommendations (Koistinen and Äijälä 2005).

3.4.3 Procurement cost of whole trees and multi-stem delimbed shortwood

The procurement costs of fuel chips from young stands, when applying the abovementioned restrictions for logging sites, were calculated for a hypothetical plant located in Jyväskylä (IV). The logging costs at the sample plot stands of NFI were calculated using the productivity models and cost parameters described in Chapters 2.3 and 2.4. The transporting costs were calculated as a function of transport distances from municipalities in the procurement area to Jyväskylä. The per-stand procurement cost of chips at the Jyväskylä plant was calculated as a sum of logging, chipping, transporting and overhead costs. Figure 14 illustrates the marginal costs as a function of harvested volume.

The available volumes and procurement cost data of fuel chips were summarised and data was sorted according to the procurement costs. The cumulative volume of fuel chips at marginal procurement cost was calculated for four harvesting alternatives and cost at plant was expressed as a relative value (IV). The marginal procurement cost was 100% when the annual procurement volume was 10 000 m³ and trees were harvested using the whole-tree method in all sample plot stands of the NFI (Figure 14).

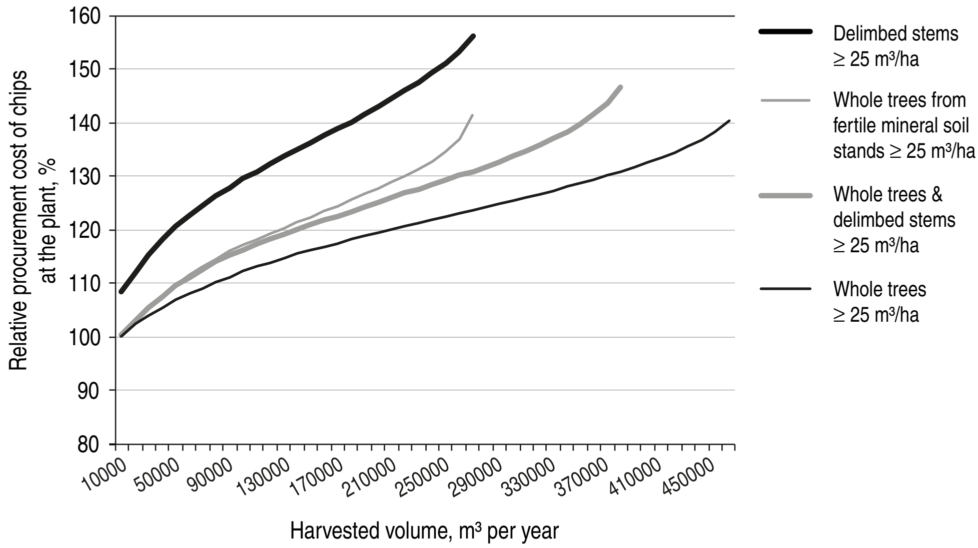

Figure 14. The relative procurement cost of chips around Jyväskylä when using alternative cutting methods and stand selection criteria.

The procurement costs were the lowest for whole-tree chips and the highest for multi-stem delimbed shortwood chips if the stand selection criteria of soil type or habitat were not used (Figure 14). When the annual procurement volume of chips was 100 000 m³ the marginal cost of multi-stem delimbed shortwood chips was 15% higher compared to the procurement cost of whole-tree chips. If the whole-tree harvesting operations were limited only to fertile mineral soil stands, the procurement costs were the second highest and the costs increased steeply, especially in the case of large procurement volumes. When combining the procurement of both whole-tree and multi-stem delimbed shortwood chips the procurement costs were the second lowest due to the increased harvesting potential. The cost difference compared to whole-tree harvesting was 4% when the annual procurement volume of chips was 100 000 m³ (Figure 14).

3.5 The decision hierarchy for choice the method for harvesting energy wood from young forests

The Analytic Hierarchy Process (AHP) is a widely used Multiple Criteria Decision Support (MCDS) method that is popular in many application fields, including forestry (e.g. Lauhanen 2002, Kangas et al. 2008). Basically, the AHP is a general theory of decision-making and measurement of preferences based on several mathematical and psychological principles. In the method, a hierarchical decision scheme is constructed by decomposing the decision problem in question into decision elements: goals, objectives, attributes and decision alternatives (Kangas et al. 2008). The general goal of the decision problem is at the top of a decision hierarchy, and decision alternatives constitute the lowest level (Kangas et al. 2008).

The importance of the decision elements is defined by pairwise comparisons with regard to each element above them in the hierarchy (Kangas et al. 2008). Comparisons are made at each level of the hierarchy. In making the comparison, the questions asked are: Which of the two factors has a greater weight in decision making, and how much greater is its weight? Which of the two decision alternatives is preferable with regard to a certain decision attribute? (Kangas et al. 2008). In the pairwise comparison, the decision-maker has the option of expressing preferences between the two elements, such as:

- Equal importance or preference of both elements (1/1)
- Weak importance or preference of one element over another (1/3 or 3/1)
- Essential or strong importance or preference of one element over another (1/5 or 5/1)
- Demonstrated importance or preference of one element over another (1/7 or 7/1)
- Absolute importance or preference of one element over another (1/9 or 9/1)

The decision-maker's preferences on decision elements are translated into numerical values (Kangas et al. 2008). Based on these comparisons, an additive model on a ratio scale describing the preferences of the decision-maker and priorities of decision alternatives with respect to the objectives or attributes is then estimated (Kangas et al. 2008). The model is called a priority function. The decision alternative producing the greatest priority is considered the "best" and most satisfactory (Kangas et al. 2008). Differences in measurement scales and units do not present any difficulty when the AHP is used, because the method is based on direct comparison between the significance and preference of each pair of decision elements without using any physical units (Kangas et al. 2008). Thus, the AHP can deal with both qualitative and quantitative attributes.

A decision tree was formed of the various factors impacting on the selection of an economically, ecologically and socially sustainable harvesting method when harvesting energy wood from young stands (Figure 15). The decision alternatives (i.e. the harvesting methods applied in entrepreneurial harvesting of energy wood) were as follows:

- Motor-manual felling-bunching of whole trees and forwarding of whole trees using a forwarder
- Whole-tree logging using a harwarder
- Mechanised felling-bunching of whole trees with a harvester equipped with a simple accumulating felling head and forwarding of whole trees using a forwarder
- Cutting of whole trees with a single-grip harvester capable of multi-tree handling, and forwarding of whole trees using a forwarder
- Cutting of multi-stem delimbed shortwood with a single-grip harvester capable of multi-tree handling, and forwarding of multi-stem delimbed shortwood using a forwarder

The aim in the selection of the decision criteria was to maximise their scope, i.e. to take into account the needs of the wood-harvesting entrepreneur, the harvesting organisation, the operators, the forest owners, the chip consumer and the community. The following were set as decision criteria in the decision tree (Figure 15):

- Harvesting costs at the roadside storage
- Minimisation of the harmful consequences of wood harvesting
- The socio-economic impacts of wood harvesting
- The quality requirements imposed on the to-be-chipped wood material
- Controlling of the harvesting operation and delivery logistics
- Availability of wood in the vicinity of the end-use facility

The decision attributes of the decision criterion "Harvesting Costs at the Roadside Storage" were as follows: the production capacity of the wood-harvesting chain, hourly operating costs of the machines, annual work volume and integration. The decision attributes of the decision criterion "Minimisation of the Harmful Consequences of Wood Harvesting" were as follows: the amount of nutrient losses in connection with wood harvesting, damage along the strip road and injuries caused to the retention stand, and stump treatment. The decision attributes of the decision criterion "The Socio-Economic Impacts of Wood Harvesting" were as follows: subsidy policy and adapting the wood-harvesting method to changes in the subsidy conditions, job-creation value, value formation within the harvesting site of the harvested wood and the stress imposed by wood-harvesting work. The decision attributes of the decision criterion "The Quality Requirements Imposed on the to-be-chipped Wood Material" were as follows: the drying of wood and the moisture percentage of the wood, the chlorine and alkali concentrations of the wood material, homogeneity and amounts of stones and other such foreign objects in the storage stacks (Figure 15). The decision attributes of the decision criterion "Controlling of the Harvesting Operation and of Delivery Logistics" were as follows: the measurability of the wood material and the accuracy of measuring, the efficiency of long-distance transportation of the non-chipped wood and the efficiency of the chipping of the wood material. The decision attributes of the decision criterion "Availability of Wood in the Vicinity of the End-use Facility" were as follows: willingness to sell wood, wood-harvesting instructions and criteria applied when selecting sites for harvesting (Figure 15).

When comparing the wood-harvesting chains in terms of different decision attributes, the number of incidents of damage caused by harvesting is influenced by factors such as the amount of lop-and-top accumulating over the strip roads, the weight of the harvesting machines and the number of repeated runs along the strip roads. The efficiency of transportation of non-chipped wood and the alkali and chlorine concentrations of fuel chips depend on whether or not the harvested wood has been delimbed. The production capacity of the wood-harvesting chains is influenced by the productivity of both cutting and forwarding. Wood-harvesting instructions, on the other hand, may include the requirement that energy wood must be delimbed at the stand or that both industrial wood and energy wood must be harvested in order to enhance wood sales revenue. Direct loading of the felled trees when using a harwarder reduces the risk of stones and mineral soil being carried over into the storage stacks. When using a measuring method based on scaling, the error resulting from wood drying is at its smallest in the harwarder method as then the harvested wood is always weighed immediately after cutting. In locations with high unemployment, labour intensiveness is a socioeconomic advantage while in a situation where there is a shortage of labour it is advantageous to minimise the labour input per cubic metre of harvested wood. Monotonous or physically heavy work adds to the stressfulness of the work.

Decision-making involves the decision-maker's likes and dislikes, and seeking a balance between different viewpoints, needs and objectives. The significance of the unit costs of wood harvesting are often emphasised when selecting the wood-harvesting method (see publications III and IV). However, one should also take into account decision objectives other than money when seeking an economically, ecologically and socially sustainable method in the harvesting of energy wood from young stands.

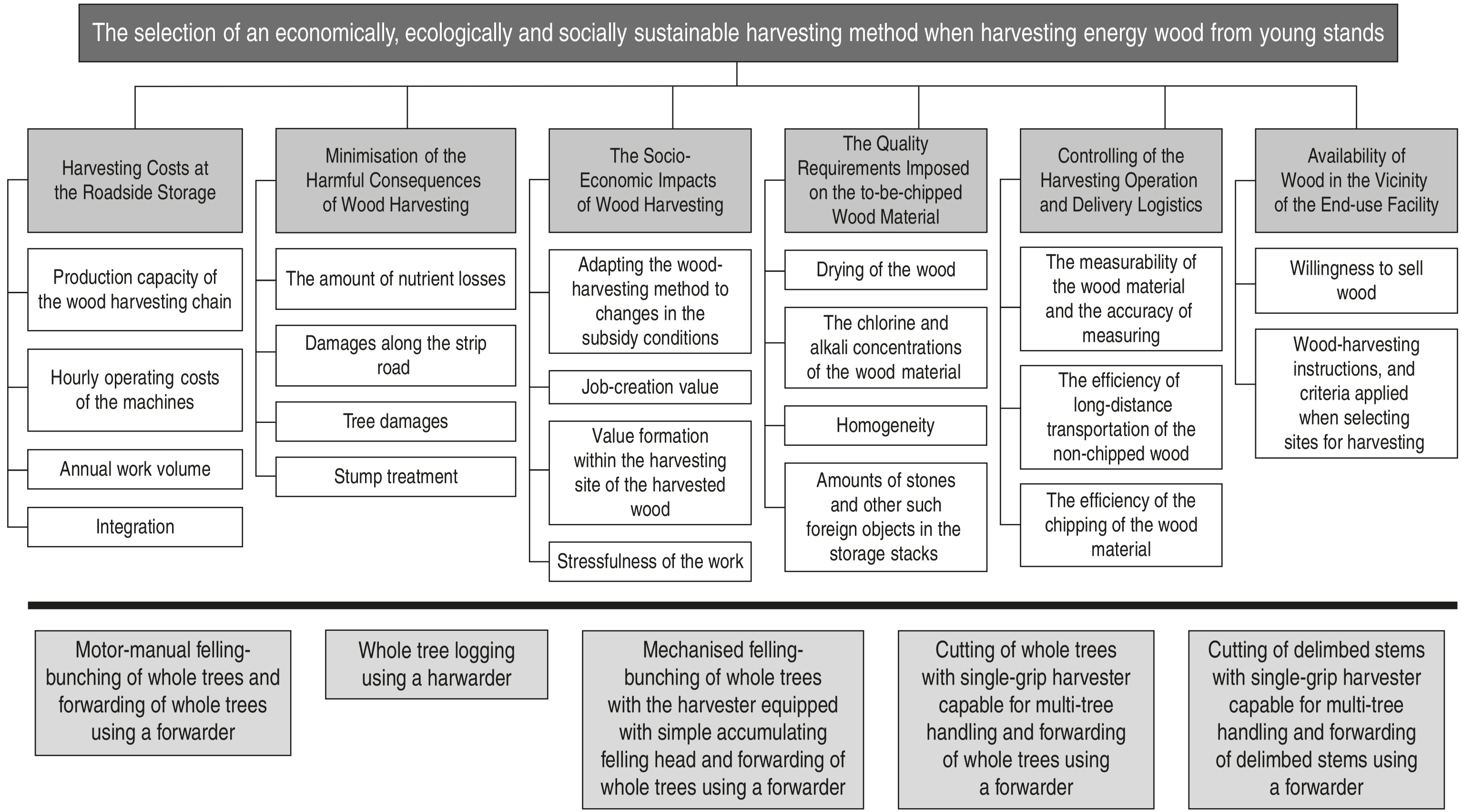

Figure 15. Decision tree for selecting the method for harvesting energy wood from young forests

4 DISCUSSION

4.1 Relevance, validity and reliability

The presented results provide productivity estimates in typical Finnish energy wood thinning conditions as well as for cost calculations and different types of simulation and modelling purposes. It is valuable information when planning thinning wood procurement activities, investments or allocating machine resources. Regression models are also needed when developing and analysing machines and working methods.

Studies III and IV were published in 2008 and 2010, which means that the absolute unit costs and operating hour costs are no longer perfectly valid in the year 2012, because e.g. the prices of machines and spare parts as well as the salary, service, insurance, administration and work supervision, lubricant and fuel costs tend to increase year by year. The cost data used in studies III and IV can be updated to the current cost level with the cost index of forest machinery and vehicles produced by Statistics Finland (http://www.stat.fi/til/mekki/yht_en.html). The "Cost index of forest machinery and vehicles" describes changes in the cost factors of prices of forest machinery and vehicles. The types of forest machinery for which indices are produced are forwarders and harvesters. A separate cost index is additionally produced for wood chippers. The monthly publication of the "Cost index of forest machinery and vehicles" also includes point figures of the cost index for truck combinations (http://www.stat.fi/til/mekki/yht_en.html).

The results reported in this paper were based on the output of one operator per machine/study and therefore they do not cover the whole range of factors affecting productivity (I, II, III). There are differences in human factors, such as the driver's motor skills, work planning and the decision-making process at the stand, which has an effect on productivity (Ovaskainen et al. 2004). All the workers involved in the studies were classified as skilled and motivated (I, II). However, it is evident that the number of experienced operators available for the study was rather limited, especially in the early phase of developing new methods and devices. In order to guarantee the reliability of the reported observations the results must be compared to the results of similar case studies and efforts should be made to verify the observed phenomenon (Hellström and Hyttinen 1996).

According to Yin (2003) a fatal flaw in doing case studies is to conceive of statistical generalisation as the method of generalising the results of the case study. This is because cases are not statistical sampling units and should not be chosen for this reason. The right mode of generalisation is analytic generalisation in which a previously developed theory is used as a template for comparing the empirical results of the case study. If two or more cases are shown to support the same theory, replication may be claimed (Yin 2003).

The time studies focused on the effective time (E_0h), which is only part of the total working time. The lengths of delays (e.g. breaks and machine service/repair) were measured but not included in the data analysis, since the studies were too short to obtain an accurate estimate of general delay times in logging work (I, II). The operating hour productivity ($E_{15}h$) coefficients for logging machines were based on estimates by the author who participated in the field studies, as follow-up study data from pre-commercial thinnings was not available and the data from the roundwood harvesting was considered invalid for this study (III). It is obvious that the mechanical availability (MA) of logging devices for whole trees is higher compared to the MA of industrial roundwood logging equipment due to, for example, the simpler structure of felling heads or combi-grapples with fewer components (III). Nevertheless, the results give estimates for the performance in the harvesting of small-diameter trees for fuel even though the harvesting devices and working methods were still under development during the time studies.

Innovation is the creation of better or more effective products, processes, services, technologies or ideas (e.g. Apilo and Taskinen 2006). Innovation differs from invention in that innovation refers to the use of a new idea or method (e.g. Apilo and Taskinen 2006). Innovations may be classified into radical and incremental innovations according to their degree of novelty. A radical innovation is a more profound change in the production process whereas an incremental innovation means an improvement to an existing product or process (e.g. Apilo and Taskinen 2006). The development of mechanisation in thinning wood harvesting for fuel has features of both radical innovation and incremental innovation. Mechanisation of energy wood harvesting in early thinnings was the radical innovation whereas the implementation of mechanisation was undoubtedly the incremental innovation, since the same base machinery as in roundwood harvesting is used in logging operations.

According to the law of discontinuous evolution (Samset 1992), technical development proceeds stepwise in the case of a single job. The nominal costs of the conventional method increase and the only way to decrease the operational costs is to introduce a new method by either using a new working method, organising work in a new way or introducing new equipment (Samset 1992). The four stages of discontinuous evolution are: 1. Price pressure. 2. Developing new methods. 3. Introducing the developed new method. 4. Widespread adoption of the developed new method in practical forestry.

During the time studies, we were in stages 2 and 3 of the evolution of mechanised harvesting, and currently we are working towards the widespread adoption of the developed new methods in practical forestry. The productivity of work methods should increase if one wishes to maintain a sound financial situation, because competitors are also developing their methods (Harstela 1993). According to Björheden (1997), when new methods are competing against existing and well-established ways of doing work, the risk is that the new method is ruled out although it has the potential of becoming the most productive, given the same amount of time for running in.

Björheden (1997, 2001) observed over several years a long-term increase in payloads in truck transporting of undelimbed tree sections. He suggested that the observed growth of payloads is mainly a result of improved operator skill. Hypothetically, the linear trend may then be interpreted as resulting from the increased ability of the operators to load tree sections in an efficient way thanks to mechanical training. According to Björheden (1997, 2001) the learning-by-doing phase of operators may be more prolonged over time than generally assumed.

Junginger et al. (2005) noted that the production costs of primary forest fuels have declined over the last three decades in Sweden in step with the growth in their use. Results showed that the main cost reductions were achieved in forwarding and chipping, largely due to learning-by-doing, improved equipment and changes in organisation. According to Junginger et al. (2005) the experience curve concept can be used to describe the cost reduction trend when assessing the future of forest chip production development.

Mechanised cutting enables the felling and bunching of whole trees into large grapple loads (II). In addition the bunching takes place closer to the strip road, which clearly improves the output of forwarding, thereby helping to reduce costs (II, III). The importance of the grapple load has also been clearly demonstrated in earlier roundwood forwarding studies (Kahala 1979, Gullberg 1997, Väkevä et al. 2003, Brunberg 2004, Väätäinen et al. 2006, Nurminen et al. 2006). According to Nurminen et al. (2006), loading is most effective with high timber volumes and from large piles, because this makes it possible for the operator to load full or almost full grapple loads of timber. When there is enough of an increase in timber volume at the loading point, the loading conditions become excellent as the whole capacity of the grapple load can be utilised. The importance of pile and grapple load size to loading is emphasised in thinnings where the volume of removed timber is typically small and piles are scattered alongside the strip road (Nurminen et al. 2006).

Belbo (2010) studied the productivity of a small multi-tree felling head (Nisula 280E) mounted on a farm tractor with a timber trailer when harvesting small trees in energy wood thinning of a mixed stand of spruce and birch. Belbo (2010) found out that the direct loading method had the highest productivity when more than 0.1 m^3 were collected in the felling cycle. For smaller grapple loads it was beneficial to collect the trees in larger piles on the ground before loading onto the trailer (Belbo 2010).

The two-machine system was found to be the most cost-competitive logging system in precommercial thinning thanks to both the efficient cutting and, especially, forwarding work in this study (III). In motor-manual worker-based logging the costs of cutting were equal to those of the mechanised system, whereas for forwarding the costs were almost double. The logging costs were found to be highest when using the harwarder system, but for larger tree volumes and removals the costs were almost equal to those of motor-manual worker-based logging (III). Reaching the cost-competitiveness of harwarder systems calls for improvements to the logging machines and devices as well to the working techniques (e.g. direct loading) of the harwarder (III).

In the study of Björheden et al. (2003), forest fuel systems based on motor-manual work were the most competitive in the smallest diameter stands. According to the study of Metsäteho (Kärhä et al. 2006, Kärhä 2006) the harvesting costs of the harwarder and two-machine system were similar. Nevertheless, the results indicated that the harwarders are the most competitive in harvesting sites where the forwarding distances are short (<150 m), the whole trees to be harvested are relatively small (< 20 litres) and the total volume of whole trees removed is relatively low (< 55 m^3/ha or < 100 m^3/stand).

In the study of Rieppo et al. (2011), logging based on motor-manual cutting of whole trees was found to be more cost-competitive than harwarder-based logging. The combination of motor-manual and mechanised work proved to be very competitive in the thinning of young forests (Rieppo et al. 2011). When comparing work methods, the cutting of trees either in the entire cutting area or in the area between the cutting trails was carried out by forest workers, in which cases the harwarder performed either only the terrain transport or the cutting of strip roads as well as the terrain transport, respectively. These methods were compared with entirely mechanised harvesting. Methods based on a combination of motor-manual and mechanised work were 20–40% less expensive than the entirely mechanised method. This is because motor-manual cutting still constitutes a very cost effective working method compared to the mechanised cutting of energy wood (Rieppo et al. 2011).

The two-pass system requires the harwarder to drive twice on the strip road in the stand: first reversing into the forest while opening the strip road and then driving back while thinning and loading the processed trees (I, Kärhä et al. 2006, Kärhä 2006). According to Björheden (1999), in roundwood harvesting, the total travel distance of a two-machine system was 4.5–5.0 times and with a harwarder 2.5–3.0 times the total length of the strip roads. In the Finnish thinning comparison, the distance travelled with a harwarder was 309 m m^{-3} and 15 450 m ha^{-1}, and with a two-machine system it was 326 m m^{-3} and 16 300 m ha^{-1} when harvesting industrial roundwood (Sirén and Tanttu 2001). The differences in first thinning conditions showed that the harwarder fell short of its capacity to combine work elements in practical work, even though the structure of the base machine should have facilitated this (Sirén and Aaltio 2003).

Also a lack of foreknowledge of the stand locations and conditions limits the targeting of logging systems to the stands that are the most optimal for harwarders (Jylhä et al. 2006, Väätäinen et al. 2007). According to the study of Väätäinen et al. (2007) the harwarder was the most cost-competitive system in 11.7–22.44% of all stands or 1.9–7.5% of the total harvested roundwood volume.

In this thesis the comparison study was made at the stand level or regional level (III, IV), which meant that the normal fluctuation of interactions, for example, in cutting, forwarding, chipping, transporting and receiving of fuel chips at the plant were not considered. The fluctuation of interactions directly affects the degrees of utilisation of machines and vehicles and also the number of machines and vehicles required. In this study, the fact that the normal fluctuation of interactions was not considered meant that the hourly costs of machines and vehicles were constant when making sensitivity analyses on the basis of removals at the stand as well as the forwarding or transporting distance (III).

Several forest technology studies have noted that interactions leading to waiting and queuing result in increased costs (e.g. Kuitto and Rieppo 1993, Asikainen 1995, Väätäinen et al. 2000, Väätäinen et al. 2005). For example in the cost of chipping and transporting the bias varies between 12–20% (Asikainen 1995) depending on the transportation distance if the interactions of chipping and transporting capacity are not considered. In order to get more realistic information on the real-life situation, discrete-event modelling of procurement systems in the prevailing operating environment is required (Asikainen 1995). The utilisation of detailed stand data on raw material resources with spatial information improves the accuracy of the results (Asikainen et al. 2001, Ranta 2002, Väätäinen et al. 2007).

Reliable knowledge of energy wood resources and procurement costs is needed when planning new plant investments (Möller and Nielsen 2007) or making decisions on both a strategic and operational level. In this study, by using the sample plot data of NFI9, it was possible to perform a detailed regional plant-specific chip procurement costs and availability analysis when using alternative cutting methods and stand selection criteria (IV). The calculation method enabled the use of time consumption functions for different production stages linked with worksite factors for different supply chains (IV). One of the themes of this study was the modification of the methodology used in the supply cost estimation of logging residue chips for use in thinning conditions (Asikainen et al. 2001, Ranta 2002). The results of this thesis concerning the factors affecting the productivity of the logging systems were logical, and the results concerning the procurement costs of chips were reasonable (III, IV).

Objectively sampled and measured NFI plots guarantee unbiased estimates of forest resources within large areas and conventional forestry attributes can be scaled down to a municipality level in multi-source NFI (IV). However, in this study scaling down poses a problem: It was assumed that the development-class level proportion of energy-wood stands would be constant within a forestry centre, which is not always the case. The same problem was faced when estimating the available volumes with different stand selection criteria. The habitat types within a municipality were assumed to be distributed similarly as within the forestry centre (IV).

It is easy to see that estimating the available volumes of small-diameter thinning wood is neither trivial nor unambiguous (IV). Firstly, the potential depends heavily on the selection criteria set for sample plots. If, for example, the minimum concentration of energy wood is raised to 40 $m^3 ha^{-1}$, the potential is reduced by 20% at the national level (Anttila et al. 2008). Secondly, the potential depends on the limits for industrial roundwood. Here all trees smaller or equal to 9.5 cm at breast height were deemed to be non-industrial wood. On the one hand, usually one pulpwood bolt can be obtained even from trees with a dbh as low as 8 cm.

Furthermore, the available volume includes all the tendings and thinnings that can be done within the next five-year period according to silvicultural guidelines (Luonnonläheinen metsänhoito – Metsänhoitosuositukset, 1994). The available volume is thus the technical potential that would be available if all recommended tendings and thinnings would be carried out and all the wood would come to the market. Further, no predictions regarding the future development of forest resources were made (IV).

In the present study the whole potential was treated as an integral entity despite the organisational territories of procurement organisations. In practice, potential calculations are made separately for each forest company or alliance. This will significantly decrease the potential at the plant level and increase procurement costs because of the need for a larger procurement area to satisfy demand (Ranta 2005). Furthermore, the estimated potential did not take into account the consumption of forest chips by existing plants. In plant-specific studies, the present use must be subtracted from the total potential in order to determine the available potential (IV).

4.2 Generalisation of the results

According to current forestry recommendations (Äijälä et al. 2010) whole-tree harvesting should be avoided in ecologically sensitive sites. However, harvesting of multi-stem delimbed shortwood is possible also in these sensitive sites since the nutrient-rich branches are left at the site. As a result the regional forest energy potential actually increases and procurement costs decrease when applying both multi-stem delimbed shortwood and whole-tree harvesting and when compared to a situation where trees are harvested only as whole trees and harvesting is limited only to fertile mineral soils (IV). Intelligent selection of harvesting methods for different stands enables minimising the transport distance and controlling the procurement costs (IV).

Laitila and Väätäinen (2011) found that the cost of whole-tree and multi-stem delimbed shortwood chips were at the same level when the breast height diameter of the harvested trees was 11 cm (pine) or more. The cutting of whole trees is cheaper, but the cost difference diminished as a function of tree size. The productivity of transportation and chipping of multi-stem delimbed shortwood was significantly higher compared to whole trees (Laitila and Väätäinen 2011). Furthermore, delimbed wood is easier to handle from a logistics perspective. Delimbed material produces uniform fuel stock devoid of needles and branches, which may be a benefit especially at some power plants with a restricted capability to handle high levels of chlorine and alkali metals contained in the branch material (Nurmi and Hillebrand 2007).

A single-grip harvester head that is capable of single- and multi-tree handling enables cutting of trees into different assortments according to market prices and product specifications, and this can increase the value of recovered material at the stand (Nurminen et al. 2009, Spinelli and Magagnotti 2010, Iwarson Wide 2011). The number of different assortments and grades depends on the size and form of the trees to be harvested and on the price of the different assortments. A cutting method that maximises the value recovery is advantageous from the points of view of both from the forest owner and wood processing industry.

From the contractor's point of view, a single-grip harvester head that is capable of single- and multi-tree handling seems appealing due to its versatility (IV). It can be used for both energy wood and industrial roundwood harvesting with small modifications. Logging sites are often comprised of several sections and this kind of multi-functional machine might reduce the need for machine transfers and increase operational efficiency. According to the study of Kärhä (2006), cutting productivity was higher with felling-bunching heads than with rollerfed harvester heads when the marked tree size was below 8 litres. With bigger tree sizes, the cutting productivity of heads capable of feeding trees surpassed that of pure felling-bunching heads. The disadvantage of a conventional harvester head in energy wood thinning is its purchase price, which is higher compared to a felling-bunching head with a simpler structure and fewer components.

Belbo and Iwarson Wide (Belbo & Iwarson Wide 2011a,b, Belbo 2011a) studied the efficiency and economic performance of an accumulating harvester head, a guillotine-based accumulating felling head and a disc saw-based accumulating felling head. For trees larger than 20 litres, the accumulating harvester head achieved higher productivity than the two felling heads. For smaller trees, the disc saw felling head was most efficient. The lower capital cost of felling heads pushed the breakeven point between the felling heads and the harvester head from 20 litres, where the productivity was equal, to 26 litres, from which point on the conventional harvesting head was the most cost-efficient (Belbo & Iwarson Wide 2011a,b, Belbo 2011a).

Public opinion favours energy wood because it is a domestic and renewable energy source. The harvesting of energy wood may be also considered to be positive in light of its silvicultural benefits in young and dense stands (Malinen et al. 2001). Private forest owners have been generally positive towards the increased use of forest fuels, although some concerns about the effects on future yields have also been expressed (e.g. Rämö and Toivonen 2001, Bohlin and Roos 2002). According to Hakkila (2006a), preconditions for increasing the use of forest chips are the reduction of production costs, improved fuel quality and reliable delivery systems. Furthermore, the fuel must be produced using environmentally sound methods. When remembering that and the results of the present study, cutting methods capable of both whole-tree harvesting and multi-stem delimbed shortwood harvesting sound very promising.

Choosing the appropriate technology means a technology appropriate for the conditions in question (Harstela 1993). Mechanised cut-to-length harvesting with the two-machine system has proven to be the most cost-competitive and sustainable system in the procurement of industrial roundwood in the Baltic Sea region (e.g. Sirén & Tanttu 2001, Sirén & Aaltio 2003, Asikainen 2004, Gerasimov & Seliverstov 2010, Jylhä 2011). It can be argued that the same observation can be generalised even when harvesting fuel wood with a single-grip harvester equipped with multi-tree handling accessories either as a separate operation or integrated with timber harvesting. Harvesting of several assortments simultaneously or accomplishing several tasks at the same time and/or with a single machine are assumed to increase overall productivity (Asikainen 2004). Using versatile machinery in thinnings increases the flexibility of forest operations and thereby improves cost-efficiency because both roundwood and energy wood are often extracted from the same stands.

4.3 Needs for further research

The new EU regulations to promote bioenergy usage are leading to a tremendous increase in demand for forest fuel and a considerable number of new bioenergy plants will be established during the 2010s. This trend calls for developing means of improving functional reliability and efficiency of wood biomass procurement chains from the stump to the end user by applying various logistical solutions involving integrated harvesting, comminution, transportation and supply chain management. I believe that information technology will be developed to serve the needs of users and will be utilised both for operative and strategic optimisation of the fuel flows.

A smart forest biomass supply chain that extends from the forest to the consumer includes advanced logistic and quality control and fuel upgrading options. A procurement chain is like an orchestra: the instruments must be tuned and in good condition, the musicians must be able to play the right songs, and at the same tempo with the rest of the orchestra. A conductor must be able to lead the orchestra so that it plays the right songs at the right tempo at concerts. In addition, the public must be satisfied with the orchestra's performances, which guarantees payment of wages for the orchestra.

Developing the cost-efficiency of the supply involves measures such as promoting the efficient use of machine and driver resources by means of multipurpose operation of prime movers and transportation equipment, ensuring efficiency in transportation and developing logistical models (supply chain management applications) for procurement and storage. Terminals as strategic stocks will become more important in the supply chain in order to ensure delivery reliability and the consistency of the delivered fuel. Besides providing supply flexibility in the winter season, terminals can also balance out variations in transport vehicle and chipping capacity. Ergonomics must be improved in forest energy procurement because the health risks, such as dust, spores and whole-body vibrations, are greater than in the procurement of industrial roundwood.

There would be significant possibilities for cost savings in young stands if the methods and techniques with the most potential were to be fully utilised in wood harvesting (Oikari et al. 2010). Therefore we should also focus on the utilisation of proven work techniques and driver-guiding systems, and the development of efficient work modes in wood procurement through work studies and machine operators' tacit knowledge (Asikainen et al. 2011). We should also seek solutions for preventing the harmful consequences of forest chip production, especially fungal and insect damage, by developing harvesting and storage logistics (Laitila et al. 2010b).

The national Wood Energy Technology Programme was carried out by the National Technology Agency Tekes during the period 1999–2004 to develop efficient technology for small-scale and large-scale production of forest chips from small trees, stumps and logging residues (Hakkila 2004). As of January 2004, this Programme consisted of 44 public research projects, 46 industrial or product-development projects and 29 demonstration projects. Altogether, 27 research organisations and 53 enterprises participated (Hakkila 2004). The Wood Energy Technology Programme for its part has contributed to establishing a solid base for the sustainable growth of the use of forest chips. Publications I–IV of this doctoral dissertation are based on the research results of Wood Energy Technology Programme's projects PUUT28 Development of Chip Production from Young Forests and PUUT44 Harvesting Alternatives and Cost Factors of Delimbed Energy Wood. There may arise a need in the future to launch another successful programme on the lines of the Wood Energy Technology Programme to provide a boost for the bio-economy's various processes alongside conventional wood procurement for the forest industries.

Close collaboration between researchers and industry was a hallmark of all the research projects carried out in the Wood Energy Technology Programme (Hakkila 2004). Collaboration helped researchers to focus the development work on fundamental issues, speeded up the transfer of research knowledge to the players in the field and also promoted networking among the participants. The capacity for research was reinforced and know-how was deepened. Even after the Wood Energy Technology Programme ended, the consumption of forest chips has continued to grow and the targets set for the consumption of renewable energy have been raised higher year after year (e.g. Laitila et al. 2010b, Ylitalo 2011). At the same time, conventional wood consumption has undergone significant structural changes and it is estimated that the consumption of wood by the Finnish forest industries will further diminish up to the year 2020 (Hetemäki and Hänninen 2009, Hetemäki et al. 2011). According to the most recent estimates (Salminen et al. 2012) some 75% of the sustainable cutting potential of industrial wood is now being utilised, and this is assumed to mean that an increasing proportion of the energy wood accrued will be composed of stemwood of industrial wood dimensions or dimensions very close to industrial wood.

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