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Opportunities for cost mitigation and efficiency improvements through rationalization of small-diameter energy wood supply chains

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Academic dissertation

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ABSTRACT

The production of energy wood from small-diameter (DBH < 9 cm) forests in Finland through separate energy wood and integrated energy wood and pulpwood production often face cost pressures that inhibit economic viability of many operations. Systemic factors, such as small stem sizes, limited removals, and high density of young forest stands limit the efficiency of many operations resulting in low productivity and high operating costs, particularly within cutting operations.

Within the study, means to increase efficiency and mitigate costs of small-diameter energy wood and integrated energy wood and pulpwood operations by identifying optimal methods, technologies, and policy that may be applied were identified. Studies of integrated and delimbed stemwood cutting methods including the use of multi-tree handling and combined timber assortments in forest stands with stem size (DBH) of removals varying between 5-17 cm were investigated and compared against separate pulpwood production. Findings suggest that the methods provide increases in productivity and decreases in costs, particularly in < 11 cm DBH conditions. Crane scale measuring was investigated as a technical solution in timber logistics to be applied in energy wood and industrial roundwood procurement. The measuring method, used as a basis of payment, was found to provide a reliable, accurate, and cost effective method when compared with a manual timber pile measurement system. Policies, in the form of financial incentives were investigated to determine the effects of applicable subsidies on the profitability of energy wood production based on stem size of removal, finding possibilities for profitable operations with reduction in subsidies, however, with stem sizes (DBH) of removal ≤ 7 cm incentives played an important role in increasing profitability.

Cost reductions were identified through: The utilization of integrated and delimbed stemwood harvesting methods with multi-tree handling, decreasing harvesting costs by 0.1-52.4% dependent on stem size (DBH) of removal between 7-17 cm when compared to a traditional pulpwood harvesting method; Combining timber assortments providing harvesting cost reductions between 1.5-8.0% between 5-17 cm; Crane scale measurement use provided increased accuracy and a 18.2-45.5% reduction in costs when compared to a manual timber pile measurement system when dependent on estimated working volumes between 20,000-30,000 m^3; Financial incentives under the PETU system were applied increasing profit margins of integrated supply chain operations by 3.8-19.9% dependent on stem size of removal, particularly with stem size of removals between 5-7 cm.

Through rationalization of supply chains, harvesting methods, technologies, and policy which exhibit the ability to reduce costs and should be utilized throughout the whole supply chain where implementation is possible.

Keywords: Energy wood production, integrated forest operations, supply chain profitability, productivity, small-diameter forest stands, subsidies, crane scale measurement.

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Additionally, I would like to thank the Forest Industry Research School in Technology program and their participants for providing an impetus for this project, the various seminar and research trips, networking opportunities within the field of forest technology, and the numerous working meetings that were conducted. Furthermore, I would like to thank family and friends whose support throughout this process has been ubiquitous.

Helsinki, March 2014

Aaron Petty

LIST OF ORIGINAL ARTICLES

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

I Petty A., Kärhä K. (2011). Effects of subsidies on the profitability of energy wood production of wood chips from early thinning in Finland. Forest Policy and Economics 13: 575-581.
doi: 10.1016/j.forpol.2011.07.003

II Petty A., Kärhä K. (2014). Productivity and cost evaluations of energy-wood and pulpwood harvesting systems in first thinnings. International Journal of Forest Engineering.
doi: 10.1080/14942119.2014.893129

III Petty A., Kärhä K. (2014). System analyses in energy and forest product production: A case study on supply chain costs and profitability.
Manuscript.

IV Petty A., Melkas T. (2014). Economic and technical importance of crane scale accuracy: A case study on timber truck and forwarder crane scale measurement. Manuscript.

Authors' contributions

Aaron Petty was the main author and fully responsible for the data analyses and writing for all of the articles. Within Paper I, Kalle Kärhä led designing of the study providing background data on forest stand conditions and removals, and estimated supply chain cost functions, Aaron Petty conducted data analyses and the writing of the paper. In Paper II, Kalle Kärhä and partners at Metsäteho Ltd led the design and implementation of the time study and provided the relationship between stem size and removals within the study. Time study and cost calculations were determined by Aaron Petty and Kalle Kärhä in conjunction with partners at Metsäteho Ltd. Productivity and statistical analyses were determined by Aaron Petty. For Paper III, Kalle Kärhä in conjunction with partners at Metsäteho Ltd led the design of the time study and provided the relationship between stem size and removals within the study. Time and productivity calculations and statistical analyses were performed by Aaron Petty with partners at Metsäteho Ltd. Cost estimates were determined by Aaron Petty, Kalle Kärhä, and partners at Metsäteho Ltd. In Paper IV, Aaron Petty, Timo Melkas, and partners at Metsäteho Ltd jointly designed the study and determined cost parameters. Timo Melkas and partners with in the Finnish Forest Industries Federation collected data utilized within the study. Quantitative and statistical analyses were performed by Aaron Petty.

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INTRODUCTION

Development of energy wood supply chains and harvesting of small-diameter forest stands

The production of energy from forests in the form of wood chips in Finland has increased from under 2 TWh in the year 2000 to 15 TWh in 2011 with 1 TWh corresponding to approximately 0.5 million m^3 (Ylitalo 2012). In 2011, energy derived from wood chips at approximately 810 energy plants accounted for 3.9% of total energy consumption within Finland with approximately 7.5 million m^3 of wood chips derived from small-diameter forest stands, logging residues, stumps, and large-sized (rotten) stemwood (Ylitalo 2012). Combined heat and power (CHP) and other large-scale facilities consumed 6.8 million m^3 of wood chips, producing 13.7 TWh, while detached houses accounted for the production of 1.3 TWh (0.7 million m^3). Approximately 45%, or 3.1 million m^3 of the wood chips utilized in CHP facilities were derived from small-diameter forest stands which were processed from whole-trees, delimbed stemwood, and pulpwood where stem diameters at breast height (DBH) of removals are generally < 10 cm; 33% from logging residues comprising of branches and stem tops; 14% from stumps and root wood and 8% from large sized rotten stem wood (Ylitalo 2012).

Established targets in Finland look to increase the production of energy from wood chips by increasing forest chip production volumes reaching 8-12 million m^3 (16-24 TWh) by 2015 and a maximum of 13.5 million m^3 (25 TWh) by 2020, which accounts for 84% of technically available forest chip production of 16 million m^3 per annum (Helynen et al. 2007; Ministry of Agriculture and Forestry 2008a; Pekkarinen 2010). Alternate potential availability of forest chips based on the gross, techno-ecological, and techno-economic potentials in 2020 have been developed by Kärhä et al. (2010a). Following a base scenario where 57 million m^3 of pulpwood is produced, emission rights price of 30 €/t CO_2, and subsidies for forest chips from small-diameter forest stands of 4 €/MWh, the gross potential was estimated with logging residues and stumps of regeneration cuttings, as well as the cutting of whole trees from small-diameter forest stands providing a potential of 105 TWh (Kärhä et al. 2010a). The techno-ecological forest chip supply potential of 43 TWh was determined when following energy wood harvesting recommendations and utilization of integrated energy wood and pulpwood production when removals were greater than 20 m^3/ha, recovery of logging residues of 70%, 95% of whole trees from small-diameter stands, and 80-85% of stumps (Kärhä et al. 2010a). The techno-economical potential provided approximately 27 TWh, based on supply chain costs and material prices at gates of energy plants and pulpmills (Kärhä et al. 2010a).

Attaining estimated production volumes, however, requires increases in energy wood production levels from small-diameter forests effectively doubling or tripling current volumes (Ministry of Employment and the Economy 2010). Although increases in small-diameter forest stands are feasible, based on different scenarios, a number of problematic issues tied to operational environment and supply chain operations exist when producing forest chips for energy production. The primary supply chains in the production of wood chips from small-diameter forest stands in Finland include: Terrain chipping, roadside chipping, terminal chipping, and chipping at plant with the primary differences between the system is the location of comminution and transportation of material as either uncomminuted or comminuted wood chips (Kärhä 2011a). Terrain chipping entails comminution at the harvesting site; Roadside chipping by either separate chipper and chip truck for transportation, or an integrated chipper and chip truck occurs along roadside forest landings where forest chips are then transported to the energy plant; Terminal chipping comminutes whole-trees or delimbed stemwood at a selected terminal and utilizes a selected mode of transportation (truck, train, or barge) in transporting the forest chips to the energy plant; Chipping at plant utilizes truck transportation of raw material as whole-trees or delimbed stemwood to the energy plant for comminution (Kärhä 2011a).

Roadside chipping has been the preferred forest chip supply chain from small-diameter forest stands, however in the future it has been estimated that chipping at plant and terminal chipping will increase their percentage shares as forest chip supply chains due to proximity and cost efficiency (Kärhä 2011a). As of 2012, it has been estimated that roadside chipping accounted for 72% of the forest chip production supply chains from small-diameter forests, decreasing 11% from the previous year. Terminal chipping increased from 8% in 2010 to 18% in 2012, while chipping at plant increased 3% to account for 10% of total supply chains of forest chips produced from small-diameter forest stands (Strandström 2012). Estimates of the percentage shares of supply chains of forest chips from small-diameter forests by 2025 place roadside chipping as the dominate supply chain, albeit with a reduced share of 55% of total production, while terminal chipping is predicted to be 17% and chipping at plant 28% of the procurement chain (Kärhä 2011a).

However, it should be noted that supply chain systems have individual costs and benefits reliant on a variety of factors including harvesting conditions, roadside storage capacities, transportation distances, CHP storage capacity, availability of production machinery, forest chip materials, production costs, and market prices which influence the selection of the supply chain system (Kärhä 2011a; Strandström 2012). With increased production volume of wood chips the need of additional machinery and further integration of forestry industry and energy production machinery is expected to increase (Asikainen 2004; Kärhä 2011a). It is expected that through integration further rationalization will encourage efficient working methods and technologies that may be optimized by maximizing volumes transported in the forest and during road or inter-modal transportation, while minimizing storage and waiting times (Kärhä 2011a).

The challenge in producing energy wood chips from small-diameter forest stands with DBH of removals (< 10 cm) is that total production costs often exceed the paying capability of buyers at energy facilities. High supply chain costs in relation to the market price of forest chips paid at the gate of energy facilities may be seen through the study of Laitila et al. (2010) where total supply chain costs based on a roadside chipping supply chain were approximately 49.1 €/m^3 (24.6 €/MWh) utilizing a delimbed stemwood method, while whole-tree harvesting produced costs 15% lower at 41.8 €/m^3 (20.9 €/MWh) at a DBH of removal of 8 cm with removals 28.7 m^3/ha for delimbed stemwood and 41.3 m^3/ha for whole-trees. However, the mean forest chip price paid upon delivery to energy plants within Finland between the first quarter of 2013 and the fourth quarter of 2013 varied approximately 18-19 €/MWh (Metsälehti 2014).

Environment and operational research constraints

Small-diameter forest stands, which may generally be categorized as having stem size of removals (DBH) less than 10 cm (Ylitalo 2012) are prone to low removals per hectare, dense undergrowth, large proportions of remaining trees, difficult terrain, long forest transportation distances, and unproductive sites on peat and mineral soils, resulting in lower productivity within cutting operations and higher supply chain costs (Oikari et al. 2010; Kärhä and Keskinen 2011). Quality requirements of pulpwood, although not static, limit the applicability of removals in small-diameter forest stands to primarily energy wood production by means of whole-tree (stems including branches) and delimbed stemwood (excluding branches).

Adverse effects from nutrient removals, however, may limit applicability of utilization of either whole-tree harvesting in favor of delimbed stemwood when decreases in nutrient levels are of concern on nutrient poor sites. Hakkila (2005) found whole-tree harvesting to increase removal of site nutrients by 50-150% when compared to delimbed stemwood, while Stupak et al. (2008) estimated nutrient removals to be 73-89% lower than that of whole tree harvesting in Norway spruce (*Picea abies* L. Karst.) stands. Although, decreases in nutrient removals may benefit future productivity of the site, the volume of removals decreased by an estimated 35-42% (Stupak et al. 2008) and 15-50% (Hakkila 2005), further hindering harvesting productivity (Hakkila 2005; Oikari et al. 2010). In a study by Heikkilä et al. (2007), nitrogen loss in particular was found to be negligible in Scots pine (*Pinus sylvestris* L.) stands when whole-tree harvesting was performed producing an on average and 10 year's growth decline of 5%, suggesting that when thinning in Scots pine stands in Finland efforts to minimize the effects of nutrient removals from whole-tree harvesting may not be necessary.

Within Finland two to three industrial roundwood thinnings generally occur prior to a final cutting. Based on targets from Finland's National Forest Program, active management of up to 250,000 hectares of small-diameter forest stands, 250,000 hectares of first thinnings, and 200,000 hectares of second thinnings should occur per year (Ministry of Agriculture and Forestry 1999). Korhonen et al. (2007) suggest first thinnings of up to 300,000 hectares per year be implemented within the next decade. However, the average first thinnings in the 2000's have been approximately 190,000 hectares per year (~ 7 million m^3/year) accounting for on average 14% of roundwood use within the domestic forest industry (Juntunen and Herrala-Ylinen 2010; Ylitalo 2010). In 2012 alone, first thinnings represented 10.9% of total industrial roundwood harvests, equating to a volume of first thinning removals of 3.98 million m^3 (Strandström 2013).

Without active management of small-diameter forest stands, or subsequent thinnings, reduced growth rates, raw material quality and value would occur and result in an economically unviable structure for industrial roundwood production (Varmola and Salminen 2004; Huuskonen and Hynynen 2006; Heikkilä et al. 2007). Energy wood production is often a secondary consideration when performing thinning operations in small-diameter stands, while the primary aim has been to enable adequate supply and quality of industrial roundwood in the future (Jylhä 2011).

The primary limiting factor in the production of energy from forest chips is the production at a viable and competitive cost with preconditions of the reduction of production costs, improved fuel and material quality, and reliable delivery systems (Hakkila 2006). Forest chip production from small-diameter forest stands primarily rely on the utilization of whole-tree or delimbed stemwood harvesting methods where the typical removals are 40-70 m^3/ha with average stem sizes of 30-60 dm^3. Delimbed stemwood removals are estimated to be generally 15-20% lower than that of whole-trees (Kärhä 2011a), but have also been estimated to be from 15-50% lower (Hakkila 2005, Stupak et al. 2008). Thinnings in small-diameter forest stands have early on been described as both a silvicultural and harvesting problem when trying to maximize the value of operational revenues after costs and the value of the residual forest stand (Silversides and Sundberg 1988). This problem is particularly apparent within small-diameter forest stands as operational efficiency and production costs are directly associated with tree size and has been described as a classical challenge when examining the economics of operating in such conditions (Silversides and Sundberg 1988; Belbo 2010). Operational efficiency in forestry has been defined as both the utilization and economic management of the resource with values placed on outcomes (Silversides and Sundberg 1988). Productivity has been one defining metric when comparing machine technologies and working methods particularly in forest engineering research, while also providing a means to measure profitability (Haarlaa et al. 1984). Work studies including time and output studies measuring productivity, quantity per unit of output, have been central in analysis of many forest operation studies providing systematic analysis within the work process (Silversides and Sundberg 1988; Samset 1990; Lindroos 2010; Uusitalo 2010).

Within time studies, defined work elements of operations may be examined and work time recorded within each element to provide an aggregate, which may be measured against the output to produce a given productivity. Various forms of time studies have been developed within forest operations work studies. However, guidelines have been developed to create standards for time studies (Cost Action 2010), as displayed in Figure 1. Among time study methods utilized within forestry operations, comparative and correlation studies are largely utilized (Bergstrand 1987; Samset 1990) with differing objectives. Comparative studies aim to compare multiple machines or methods with other influences remaining static, while correlation studies describe the relationships between productivity and influencing factors (Lindroos 2010). However, combinations of the two are commonly utilized within studies occurring in forest environments prone to variability, so that stand conditions often characterized by average stem size (DBH) remain the same within the study for comparison (Lindroos 2010). Attaining accurate productivities is often difficult to

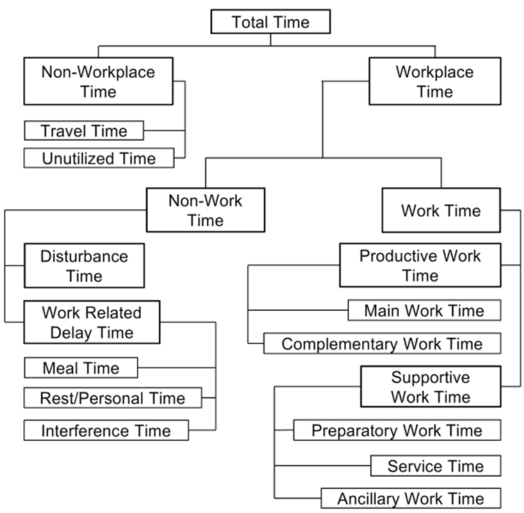

Figure 1. Adapted time study elements utilized in forest operation work studies (COST Action 2010).

achieve when acknowledging and discerning influencing factors occurring during the study (Mäkelä 1969, Samset 1990, Lindroos 2010, Purfürst and Erler 2011). Human factors alone can account for large variation in performance within time studies with operator variability found to account for 37.3% compared to environmental factors, such as tree volume accounting for 45.9% of variability when examining operator harvesting productivities under similar prescribed thinnings (Purfürst and Erler 2011).

Similarly, Kärhä et al. (2004) and Ovasikainen (2009) have found productivities of operators utilizing the same harvester to vary by up to 40%. Differences in productivities have also been assessed to be higher when operating in first thinnings compared to second thinnings (Kärhä et al. 2004) and could potentially be expressed by the relation between difficult (technical or environmental) conditions and the operator when examining productivities (Purfürst and Erler 2011). Operator blocking has been one statistical method to compensate for operator influence within comparative time studies and have commonly assumed: relative productivity between multiple work methods is independent of the operator when the same operator is utilized on all methods, productivity of one method may be anticipated on the basis of the operators productivity with another method, and that operator variation may be reduced when the same operator performs all methods analyzed (Lindroos 2010; Uusitalo 2010). However, on an individual level, blocking has not consistently proven to mitigate variability induced by the operator (Harstela 1988; Lindroos 2010) as opposed to utilization of blocking on a population level has shown operators responses to be similar albeit with large variations between individuals with homogeneity of demographic and operator experience (Lindroos 2010).

Performance ratings within correlation studies have also been utilized to reduce variability in measured productivities within time studies, although with measured trepidation as to the validity of the subjective method (Nordic agreement on...1978; Samset 1990; Samset 1992). Performance ratings within time studies that subjectively rate operator behaviour and output have been shown to correlate with long-term follow-up studies of time study outputs (Purfürst and Lindroos 2011). However, the correlation between the two also varied based on the evaluator, suggesting larger differences with wider variance in perceived normal work performance (Purfürst and Lindroos 2011). With large variations of performance with both methods on an individual level, applicability of the methods must be considered when identifying the objectives of the study (Purfürst and Lindroos 2011) and how the method may influence variation of measured productivities.

Technical development and economic considerations in energy wood production

When operation costs become too high, development of new machines and methods occurs, where work studies play a vital role in increasing operational efficiency and reducing costs (Samset 1990). With the mechanization process developing rapidly for energy wood operations over the past decade (Laitila 2012), a variety of technological and working method solutions have been developed to increase productivity and reduce operating costs within thinning operations. High harvesting costs, particularly cutting costs, from low removals and productivity often inhibit economic viability in small diameter forest stands (Kärhä 2011b). Utilization of single-tree handling alone in thinnings within small-diameter forest stands haven proven to be particularly difficult due to low removals, large volumes of under-utilized biomass and the low cutting productivity when felling single trees (Kärhä et al. 2010b).

Development of mechanized harvesting capable of multiple-tree handling (MTH) has improved productivity by reducing the number of grapple and boom movements required when compared to single tree handling (STH) (Lilleberg 1997; Brunberg 1998; Johansson and Gullberg 2002; Bergkvist 2003; Kärhä et al. 2005; Belbo 2011). When grapple and boom movements are simplified, reduction in felling and accumulation time consumption occurs within MTH (Johansson and Gullberg 2002). Increased productivity improvements through MTH have not only been limited to energy wood, but have been shown to increase productivity of pulpwood harvesting (Lehtimäki and Nurmi 2010). Multi-tree handling utilized within separate harvesting of pulpwood, whole-trees to be chipped for energy production, and delimbed stemwood for energy production has provided benefits through increased productivity and reduced operation costs. Individually each harvesting method presents challenges among which include: Applicability to sites where environmental constraints limit feasibility, low removals, utilization of pulpwood as a lower valued product, and high costs associated with either forwarding or transportation of material (Kärhä et al. 2010c). As energy wood may be harvested either in the form of delimbed or undelimbed material with harvesting solely for energy wood or in combination with industrial roundwood, MTH provides applicable benefits to both forest and energy industries. In particular, the flexibility in harvester heads capable of MTH limits the need to utilize separate grapples when harvesting both industrial roundwood and energy wood (Laitila 2012). The variety of felling heads such as those utilizing cutting blades, chain saw, circular saws, delimbing knives, and feed rollers are further improved upon by software optimizing harvesting allowing for bucking based on stem size, desired timber grade and include MTH optimizing software. Integration of both industrial roundwood production and energy wood, with the aim of reducing operational costs below that of separate procurement by increasing removals and cutting productivity has been one method to reduce costs and address some of the challenges of separate energy wood or pulpwood production. Integrated production of energy wood and pulpwood has been noted as developing due to the need of reducing harvesting costs, concerns over accumulation of logging residues on forest roads and landings, and the potential use of integrated harvesting to further assist in management of small-diameter forest stands (Hudson 1995). Increased utilization of MTH, chain flail and chipper systems, as well as the recognition of harvesting as part of the total supply chain system have led to the increased use and variety of integrated systems today (Hudson 1995).

One such system is integrated harvesting utilizing a two-pile method, where industrial roundwood and energy wood are stacked in two separate piles. Integrated harvesting under this method has previously been shown to reduce cutting costs to below those of the separate cutting of either pulpwood or energy wood based on whole-tree and delimbed stemwood for energy and forest product production (Heikkilä et al. 2005; Kärhä 2011b; Kärhä et al. 2011a). However, when examining the cost effectiveness of integrated production systems, availability of efficient harvesting systems, road accessibility and infrastructure within reasonable transportation distances, and regional market prices for raw material produced have been noted to influence the economic feasibility (Han et al. 2004; Di Fulvio and Bergström 2013). Cost pressures are particularly evident when integrated production leads to decreases in productivity in the harvesting of the higher valued industrial roundwood product (Conrad IV et al. 2013).

Productivity decreases of approximately 10% (Kärhä and Mutikainen 2008) and 35% (Di Fulvio and Bergström 2013) have been noted to occur when integrating the production of pulpwood and energy wood when compared to whole-tree cutting of energy wood utilizing MTH. Decreases in productivity when compared to whole-tree cutting occurs due to the increased time of processing and piling timber assortments, as well as the advantage of increased biomass removals that are present in whole-tree harvesting (Di Fulvio and Bergström 2013). However, within harvesting systems, productivities achieved in thinnings are often correlated with site conditions such as stem size (DBH) of removal, density of removals (Belbo 2010; Belbo 2011; Di Fulvio et al. 2011), and initial stand densities (Di Fulvio and Bergström 2013). The integrated system has the flexibility to adjust shares of either product. For this reason, delimbing of stemwood is particularly appealing, especially when operating within stem size of removals that could be applicable for either energy wood or pulpwood production. When compared to whole-tree harvesting among small stem sizes, Heikkila et al. (2005) and Laitila et al. (2010) have noted the relative cost disadvantage from delimbing, but the disparity decreased with increasing stem size of removals. Combining of timber assortments, reducing the number of timber assortments to handle has also developed as a means to increase productivity within the two-machine (harvester and forwarder) system. Manner et al. (2013) have found that increasing the number of timber assortments increases loading and unloading times within forwarding. While Nurminen et al. (2006) and Brunberg and Arlinger (2001) have noted the ability of increasing the number of timber assortments to reduce productivity.

Variation in harvesting work methods and technology improvements in harvesting heads have not been the only technology developments related to energy wood supply chains. The increased use of timber measurement methods has developed with utilization of a myriad of measuring devices at different stages of the forest supply chain. Measuring systems include harvester measuring gauges, crane scales, timber pile measuring, individual log measuring, timber sampling, picture frame measuring, and weight bridges among others (Metla 2013). The goal of utilizing measuring systems has been to further integrate forest supply chains from felling of timber to delivery at receiving facilities, and in doing so increase efficiency and reduce costs within procurement (Siry et al. 2006; Melkas and Hämäläinen 2012; Verkasalo and Karvinen 2012). Efficiency within timber measurement equates to reducing variability within measurement accuracy of assortments being handled. Reducing variability in gross vehicle weight, maximizing the volume of allowable raw material has been noted to provide the maximum cost-effectiveness within transportation (Shaffer et al. 1987; Hamsely et al. 2007). Crane scales provide a means to both increase efficiency and integration (Hujo 2006) and have recently increased their presence and applicability as a measuring system utilized on forwarders and timber trucks and trailers (Melkas 2012). Crane scales are currently utilized as a means to determine timber mass, timber payments when weight bridges are unavailable, and payments to contractors, but also as a means to ensure efficient vehicle loading (Heikkilä et al. 2004; Siry et al. 2006; Verkasalo and Karvinen 2012). Accuracy of crane scales in the context of assortments and scale types have only recently been conducted (Hujo 2006; Iwarsson Wide and Jönsson 2012), but demonstrate a reliable measuring system capable of measuring energy wood, pulpwood, and logwood utilized in both energy and forest industries.

Cost considerations within operational research

Cost considerations play an important role in comparing and examining the implications of the effectiveness of different energy wood harvesting systems to be economically viable options. Examining costs in the context of integrated energy wood and pulpwood harvesting systems and supply chains, various costing systems exist. Puttock (1995) has noted two costing systems, which include marginal and joint costing. Marginal costs can be determined, where operation costs are allocated to the conventional product, such as pulpwood. Joint costing allocates costs of the operation based on the contribution of each product (Puttock 1995). Furthermore, costing can be examined through the ability to pay, such as wood paying capability (WPC) at a kraft pulp mill (Jylhä et al. 2010), as break even analyses examining net income delivered to roadside or gate of receiving facilities (Han et al. 2004; Di Fulvio et al. 2011; Conrad IV et al. 2013; Di Fulvio and Bergström 2013), or by examining harvesting or total supply chain costs among themselves (Kärhä 2011b; Kärhä et al. 2011b).

In the broad sense of operation estimating, determining cost has been noted as the primary objective (Ostwald 1992). Labor, engineering performance data, and time estimates for selected work elements are utilized in cost estimating by multiplying total time by a wage or productive hour cost (Ostwald 1992). Operation estimating allows for operation designs to be segmented into both physical and economic elements with the purpose of establishing cost components of a supply chain, while allowing for the possibility to initiate cost reductions, provide standards for production or control, and compare different designs (Ostwald 1992). Within forest operations, profitability of harvesting systems is determined through unit costing derived from hourly productivity established through time studies and hourly operating costs (Uusitalo 2010). Unit costs of machines utilized in forest operations may be determined based as functions of a predetermined output, such as area of operation, total volume, transportation distance, ect. (Harstela 1993). Fixed and variable costs based on time and productivity estimations, as well as initial capital costs of the machine are utilized to determine cost of machinery operation. Fixed costs comprise of interest, depreciation and insurance, labor, and expenses accrued due to work organization and management, while variable costs include fuel, lubricants, repair and maintenance, work and travel compensations through wages and allowances (Harstela 1993; Uusitalo 2010). Variability within the cost structure is introduced due to estimates on factors including machine availability and utilization rates, depreciation periods, applied interest rates, labor, and overhead costs utilized when determining fixed and variable costs (Harstela 1993; Uusitalo 2010). Assumptions are required within many aspects of cost estimating, which in turn limit the ability in determining the actual operation costs when examining systems where the entirety of specific machine performance and economic variables are not available. Belbo (2011) has noted the potential of assumptions such as economic life span, variation in wear and tear on machinery, and moving costs of machinery as assumptions with the potential to reduce accuracy of the cost estimate. Furthermore, cost estimations and components of estimations of machinery operations utilized within supply chains can be based on previously performed studies, inventory data, or road transportation networks to elucidate the potential costs associated when combining cost components of a supply chain, i.e. harvesting, forwarding, transportation, as in studies of Latila (2008), Laitila et al. (2010), Ringdahl et al. (2012), Kärhä et al. (2011b).

OBJECTIVES

This dissertation looks to incorporate findings of the research conducted in papers (I-IV) by focusing on aspects from harvesting of small-diameter trees to delivery at gate of either pulp mill or energy facilities, providing a system analysis approach to aspects of the whole supply chain. The objective of the dissertation is to identify means to increase efficiency of small-diameter energy wood operations by identifying optimal methods, technologies, and policy that may be applied and in turn increase efficiency, reliability, and reduce costs.

The framework of the dissertation utilizes the applied analytical methods within conducted research in papers (I-IV) to rationalize various aspects of small-diameter energy wood supply chains by focusing on areas where efficiency improvements are shown to improve the economic feasibility of energy wood production. The term, rationalization, is used in the context of applying the principles of scientific management to operations to achieve the desired result of increased efficiency. Efficiency improvements presented as research topics are combined to describe areas where the rationalization process throughout supply chain, from cutting to delivery, produces the desired effect. The objectives of the individual studies (I-IV) were defined as:

1) Compare the total production costs of forest chips utilizing whole-tree harvesting of small-diameter forest stands with and without subsidies offered for the production of forest chips in Finland, while presenting the effects of variable levels of subsidies provided in the Kemera subsidy system and the ramifications of future policy changes. (Paper I).

2) Determine the productivity in harvesting separate and integrated energy wood and pulpwood systems and to compare the costs of selected systems based on stand conditions and cutting system techniques employed in the harvesting of both energy wood and pulpwood. (Paper II).

3) Evaluate the influences of pulpwood and delimbed stemwood cutting systems and subsidies offered for energy wood on total supply chain costs and profitability of integrated energy wood and pulpwood production. (Paper III).

4) Determine the accuracy of crane scale measurements of combined timber truck and trailer and forwarders within Finland when following calibration guidelines by measurements as a whole, by scale manufacturer, measuring principle, timber assortment, time period, and contractors utilized in timber procurement within Finland; Secondly, to quantify the economic importance of crane scale accuracy in energy wood and industrial roundwood procurement through reliability and costs when compared to manual timber pile measurement. (Paper IV).

When combining papers (I-IV), rationalization of forest chip supply chain operations from small-diameter forest stands were demonstrated through: 1) Policy implications in relation to supply chain costs and profitability of harvesting in small-diameter forest stands covered in papers (I and III); 2) Harvesting technologies and operational methods, which increase productivity and cost-efficiency examined in papers (II and III); 3) Integrated energy wood and pulpwood supply chains and their implications in increasing profitability covered in papers (II and III); 4) crane scale accuracy and economic importance of material measurement in forest industry procurement is elucidated in paper (IV).

MATERIALS

Forest operation time study data

Continuous time studies of cutting operations of separate and integrated pulpwood and energy wood operations as delimbed stemwood were performed in papers II and III with each study conducting time studies on six different cutting methods. Time studies were conducted on plots with areas varying between .49-.54 ha (paper II) and .13-.26 ha plots (paper III) on forest stands with relatively level terrain, high bearing capacity, and no foreign obstacles, such as rocks interfering with cutting and forwarding work. The breast height diameter (DBH) of removal and the number of stems felled were manually recorded during processing, while stem volumes were determined with the volume functions of Laasasenaho (1982). Densities of remaining trees within the study plots were inventoried after cutting operations with two inventory plots with a width of 20 meters and length of 10 meters on each study plot (Paper II) and with four circle inventory plots (r= 3.99 m) on each study plot (Paper III). Statistical comparisons of the stand conditions study plots for paper II and III were performed on the stem size (DBH) of removals (cm) and the volume of removals (dm^3) from each study plot utilizing SPSS statistical v. 20 statistical software through comparison of standard deviations, analysis of variance (ANOVA) including a Tamhane's post hoc test, and robust equality of means tests based on cutting methods.

The continuous time studies segmented the work cycles into: Moving; Boom-out, felling, delimbing, cross cutting, and collecting; Separating fractions into assorted piles; Miscellaneous; and Delays. When determining effective time consumption, stem processing times were calculated as the work cycle elements of boom-out, felling, delimbing, cross cutting and collecting, and separating fractions into assorted piles. Stem processing times per stem were determined for single and multi-tree handling by dividing stem processing time by the number of stems present per handling. Weights were assigned based on the number of stems within the collected bunch during handling and through a weighted nonlinear least squares regression, observations with higher weights were assigned greater importance within the regression procedure. Stem processing times dependent on the stem size (DBH) of removal were modeled with the SAS statistical package through the NLIN procedure (paper II) and with SPSS v. 20 statistical software in paper III. Moving times were calculated from the mean moving times and removals (trees/ha) based on the selected cutting methods in papers II and III and modeled through regression analysis as a function of the density of removals (trees/ha) utilizing SPSS v. 20 statistical software, while miscellaneous times were calculated from the mean miscellaneous times of each cutting method in paper II and the aggregate miscellaneous time for each cutting method in paper III.

Within paper II, time studies were conducted based on the following cutting methods and assortments and pile fractions:

1) Pulpwood utilizing single-tree handling with stem DBH of 7-17cm; three fractions separated by species (**Pulpwood, STH**).
2) Pulpwood utilizing multi-tree handing with stem DBH of 7-17cm; three fractions separated by species (**Pulpwood, MTH**).
3) Integrated harvesting of pulpwood and delimbed energy wood with stem DBH of 5-17cm; utilization of multi-tree handling with stems < 10 cm DBH and single-tree handling with stems ≥ 10 cm; pulpwood sorted into three fractions by species and one fraction for energy wood (**Integrated, 10 cm**).
4) Integrated harvesting of pulpwood and delimbed energy wood utilizing multi-tree handling with stem DBH of 5-17cm; pulpwood sorted into three fractions by species and one fraction for energy wood (**Integrated**).
5) Delimbed stemwood utilizing multi-tree handling with stem DBH of 5-17cm; three fractions by species (**Delimbed stemwood, MTH, SF**).
6) Delimbed stemwood utilizing multi-tree handling with stem DBH of 5-17cm; combined fractions (**Delimbed stemwood, MTH, CF**).

The time studies of paper II were conducted in Eastern Finland, near the city of Leppävirta (62°30´N, 27°47´E) on forests of Metsähallitus (State Forest Enterprise). A Ponsse Ergo harvester weighing approximately 19 tonnes with an attached Ponsse H7 harvester head (~1.2 tonnes) and Ponsse C4 crane of 10 meters was utilized in the time study. Multi-tree handling was conducted by Ponsse's OptiWin 4.602 information system software by a multi-tree handling control procedure. The operator had considerable (> 10 years) experience in harvesting work concerning thinning operations and a half year of experience in integrated and delimbed stemwood cutting. When utilizing multi-tree handling in pulpwood cutting, however, the operator was limited in experience (< 2 months). Pine and spruce pulpwood and all delimbed stemwood stems were processed at lengths of 2.7-5.0 m, while birch pulpwood was processed at 2.9-3.0 m. The minimum top diameters varied by assortment and species with the minimum top diameter of pine and birch pulpwood at 6 cm, spruce pulpwood at 7 cm, and delimbed stemwood varying between 2-3 cm.

A Ponsse Buffalo forwarder utilizing a Ponsse LoadOptimizer v.1.2.2 crane scale was utilized in the forest haulage of cut wood, which was performed in separate loads for each time study plot. The mass of timber was measured by crane scale and converted into volume (m^3) utilizing green density functions of the Ministry of Agriculture and Forestry (2010) and Lindblad et al. (2010), which include: pine pulpwood: 930 kg/m^3; spruce pulpwood: 846 kg/m^3; birch pulpwood: 889 kg/m^3; delimbed stemwood of combined species (pine, spruce, and birch): 900 kg/m^3. In total, approximately 3,313 stems were processed in the time study among the six cutting methods with a total volume of 210 m^3. Of the six cutting methods, the average density of removal was 1,045 (stem/ha), stem size (DBH) of removal 10.9 cm, and removal of 67 m^3/ha. Harvested species were made up of approximately 47% Norway spruce (*Picea abies* (L.) Karst.), 38% Scots pine (*Pinus sylvestris* L.), and 15% deciduous, which were almost exclusively birch (*Betula pubescens*).

In paper III, the time studies were conducted with the following cutting methods, assortments, and pile fractions:

1) Pulpwood utilizing single-tree handling with stem DBH of 7-17cm; three fractions based on species (**Pulpwood, STH**).
2) Pulpwood utilizing multi-tree handling with stem DBH of 7-17cm; three fractions based on species (**Pulpwood, MTH**).

3) Integrated pulpwood and delimbed energy wood utilizing multi-tree handling with stem DBH of 5-17cm; pulpwood fraction as a separate pile than energy wood (**Integrated**).
4) Delimbed stemwood utilizing single-tree handling with stem DBH of 5-17cm; combined fractions (**Delimbed stemwood, STH, CF**).
5) Delimbed stemwood utilizing multi-tree handling with stem DBH of 5-17cm; combined fractions (**Delimbed stemwood, MTH, CF**).
6) Delimbed stemwood utilizing multi-tree handling with stem DBH of 5-17cm; three fractions based on species (**Delimbed stemwood, MTH, SF**).

The time studies of paper III were conducted in a first thinning on forest stands located in proximity to Savonlinna (61°52´N, 28°53´E) in Eastern Finland. The studies were conducted with a Valmet 901.4 harvester weighing approximately 14,490 kg and a Valmet 350.1 harvester head (~1,000 kg) with a CRH-15 crane of 10 meters. Multi-tree handling was conducted by software utilizing a MaxiXplorer control and information system. The harvester operator held 12 years of experience working with thinning operations and 8 months experience in delimbed stemwood cutting, however, did not have previous experience utilizing integrated cutting. Stems were processed to lengths (m) and minimum top diameters (cm) by assortment. Pine and spruce pulpwood was cut to lengths of 2.7-4.5 m, birch pulpwood from 2.7-3.0 m, and delimbed stemwood between 2.7-3.0 m. Minimum top diameters were not established for delimbed stemwood, while pine pulpwood was 6 cm, spruce pulpwood 7 cm, and birch pulpwood 5 cm in diameter.

A Valmet 830.3 forwarder (~10,500 kg) conducted forest haulage, performing separate loads for each study plot. Timber weight, measured by a Komatsu crane scale, was converted into volume (m^3) applying green density factors of the Ministry of Agriculture and Forestry (2010) and Lindblad et al. (2010): Pine pulpwood: 954 kg/m^3; spruce pulpwood: 869 kg/m^3; birch pulpwood: 917 kg/m^3; delimbed softwood: 930 kg/m^3; delimbed hardwood 900 kg/m^3. In the time studies of the six cutting methods, 1,875 stems were processed with Scots pine accounting for 47%, Norway spruce 7%, and birch 51% of the total removals. The total volume of timber removed was 110 m^3 with an average density of 1,948 stems/ha, stem size (DBH) of removal of 12 cm, and roundwood removal of 109 m^3/ha.

Crane scale measurement data

Crane scale measurement data from timber truck and trailers and forwarders based on delivery information of companies within the Finnish Forest Industries Federation for the time period of 2011-2012 was utilized to determine crane scale, or loader scale accuracy within paper IV. The paper includes two crane scale measurement studies segmented into 1) Timber truck and trailer crane scale measurement data, and 2) Forwarder crane scale measurement data. Average differences and standard deviations of observations were utilized measure accuracy of defined categories including the whole data sets and weight classifications, scale manufacturer, measuring principle, time period, timber assortments of pulpwood and logwood, and contractors.

Timber truck and trailer recorded load weight data entries totalling 65,131 observations within 2011 were collected from operative data from crane scale load and weigh bridge weightings in Finland via shareholders of Metsäteho Ltd. Recorded weightings were determined by timber transportation contractors and receiving customers at pulp and saw mills utilizing loader scales and weigh bridges. Recorded data for each observation consisted of: Delivery date, pulp or saw mill name, timber assortment, scale model or manufacturer, identification of contractor, loader scale weight (kg), and weigh bridge weight (kg). Outliers from the observations were filtered by means of a 99% confidence interval, where 64,479 observations were then utilized within the accuracy study. The average load size of truck and trailers within the study was 26,891 kg with load sizes varying between 50-55,000 kg. Average weight at delivery was 26,910 kg with weights varying between 50-50,760 kg. Timber deliveries were performed on average 46 times among the 322 contractors identified in the study.

Observations were taken throughout the year and time periods were allocated into quarters with the percentage share of observations as: Q1: 28.7%; Q2: 26.1%; Q3: 22.1%; Q4: 23.1%. Timber assortments of pulpwood and logwood were utilized within the study, while energy wood assortments were excluded due relatively small amount of data. Pulpwood and logwood accounted for 90.7% and 9.3% of the observations, respectively. Reported crane scale manufacturer and models were used to identify scale manufacturers, which consisted of five sets of accuracy calculations by manufacturer. Scale manufacturers and model years included: Epec LoadOptimizer (1995, 1999, 2001-2012), Loadmaster 2000 (2000, 2002-2012), Loadmaster Multi (2008-2011), Tamtron (2007-2008, 2011-2012), TB (2002, 2005). Scale manufacturers, identified by an assigned letter held percentage shares of: A: 15.9%; B: 22.4%; C: 46.4%; D: 14.9%; E: 0.3%. Utilization of a hydraulic measuring principle occurred in 84.1% of the crane scales, while strain gauge measuring was identified in 15.9% of the scales.

Within the second study of paper IV, forwarder crane scale measurement data from weekly monitoring of measurement accuracy of forwarders equipped with crane scales utilized in timber procurement was collected from January 2011 through June 2012 in Finland from members of the Finnish Forest Industries through Metsäteho Ltd. Recorded measurement data of scale model and manufacturer, measuring principle of the scale, contractor identification, test dates, control lifts, control weight (kg), and the loader scale recorded weight (kg) were taken for each of the 2,990 observations to determine accuracy. Duplicate data and observations where repeated test lifts deviated from the recommended 20 lifts of a control weight when performing scale accuracy checks were filtered from the data set bringing the total observations utilized within the study to 2,010. The average mass of the control weights (kg) was 453 kg with observed weights between 242-840 kg. Test weightings, measured by the control weight and number of repeated control weights varied from 4,840-16,800 kg with an average of 9,052 kg. Recorded loader scale weights were between 4,801-17,258 kg with an average of 9,054 kg. An average of 12.7 test weightings occurred among the 158 contractors identified within the study.

Similar to the truck and trailer data, test weighting time periods were recorded quarterly (Q1-Q4) with 23.4% of the observations falling within Q1, 35.4% in Q2, 26.9% in Q3, and 14.3% within Q4. Six crane scale manufacturers were utilized in the study and included: John Deere, Komatsu, Loadmaster, Mecanil, Ponsse, and Tamtron. Manufacturers were designated by an assigned letter within the study and included the following with their percentage share of the observations: G: 13.6%; H: 17%; I: 32.9%; J: 5%; K: 30.8%; L: 0.7%. Measuring principles identified by the crane scale manufacturer, including strain gauge and hydraulic pressure measuring principles were recorded with strain gauge measuring accounting for 49.4% of the observations and hydraulic pressure 50.6% of the observations within the forwarder monitoring accuracy study.

Cost data

Cost parameters utilized in papers I, II, III, and IV allowed for cost estimations and comparison between various systems throughout the studies.

Within paper I, aggregate supply chain costs were determined from the relationship betwen stem size of removals and density of removals utilized in a study of Kärhä (2011b). Predetermined costs of components included financial incentives, comminution, storage, and overhead costs. Financial incentives provided through the Kemera subsidies were determined by Finnish law statutes (2007) and implementation described by the Forestry Development Center Tapio (2008; 2010) and included: I. Subsidy for thinning in young stands, II. Subsidy for small-sized energy wood harvesting, III. Subsidy for chipping, IV. Subsidy for providing work clarification. Comminution and storage costs were derived from the studies of Kärhä et al. (2009; 2010b), while an estimation of overheads utilized in industrial roundwood consumption in 2009 was derived from Kariniemi (2010).

Costs represented as functions of stem size of removal, volume of removals, and transportation distance estimated through cost functions were utilized in determining selected costs of the supply chain and included: Stumpage, cutting, forwarding, and transportation cost functions. Stumpage prices were determined as a function of stem size of removals applied in Kärhä (2011b). Cutting costs were determined by dividing the estimated hourly costs per productive machine hour including < 15 minute time delays (PMH_{15}) by time consumption functions derived from models of Kärhä et al. (2006), Kärhä and Mutikainen (2008), and Kärhä (2011b). Cutting costs were modeled as a function of the stem size of removal (DBH). Forwarding costs were determined by dividing the estimated hourly costs of a forwarder with a carrying capacity of 10-12 tons (Kärhä 2006; Kärhä 2007) by forest haulage time consumption within the study of Kärhä et al. (2006) and assumed a load size of 6.5 m^3 and forest haulage distance of 300 m. Transportation costs assumed a chip truck load size of 42.5 m^3 (Kärhä et al. 2009), while hourly machine costs were based on the Truck Transportation Model of Metsäteho (Metsäteho 2010), estimating variable and fixed costs contributing to hourly machine costs. Costs were determined as a function of transportation distance.

Within papers II and III, total harvesting costs including cutting and forwarding costs were determined as a function of stem size of removal (DBH) in cutting, while forwarding costs were modeled as a function of pulpwood and energy wood (delimbed stemwood) removals (m^3/ha). Cutting costs were based on the productivity functions derived from the time studies of paper II and III, while time and productivity functions of pulpwood and delimbed stemwood forest haulage were based on models of Kärhä et al. (2006). Time consumption models for the medium sized forwarder utilized in the pulpwood forwarding costs assumed a carrying capacity of 11-13 tones, a load size of 11 m^3, and forest haulage distance of 300 meters, while integrated and delimbed stemwood cutting methods with energy wood removals utilized a smaller load size of 8.6 m^3 (Kärhä et al. 2011c; Perho 2012). Operating costs included time dependent, fixed, and variable operating costs and were estimated utilizing the Forest Machine Cost Calculation Program of Metsäteho Oy and was utilized in determining hourly machine costs of the medium-sized harvester and forwarder within the studies (Metsäteho 2012a).

Additional supply chain cost components within paper III included: Stumpage, transportation, comminution, overheads, and incentives. Stumpage prices were determined as a function of stem size for the removals based on the shares of pulpwood and energy fractions. Transportation costs of pulpwood, delimbed stemwood, and wood chips were estimated utilizing the Truck Transportation Model of Metsäteho Oy (Metsäteho 2012b) utilizing estimates of transportation times, fixed, and variable costs. Estimates of unit costs of comminution at roadside and at energy facilities were estimated based on Strandström (2012) and Hautala (2011). Overheads were determined by the average overhead costs of industrial roundwood production of the Finnish Forest Industries and Metsähallitus (Strandström 2013). Applied subsidies in paper (III) varied from paper (I), as a reorganization of subsidies offered for the production of combined heat and power occurred and will be implemented in 2015 and included an area based subsidy and a subsidy paid to heat and power facility operators after comminution (Ministry of Agriculture and Forestry 2012).

Within paper IV, measuring system costs of a manual timber pile measurement system and the crane scale system were compared based on three working volume scenarios measuring volumes 20,000, 25,000, and 30,000 m^3/year. Fixed and variable costs of both crane scale and manual timber pile measurement systems were estimated from expert opinions (Poikela 2013), while time consumption for crane scale measurement assumed a 42 week working year with machine calibration and reported estimated to 45 and 5 minutes respectively. The manual timber pile measurement system assumed roadside storage piles of 200 m^3 with the estimated total time consumption of 1.2 hours per storage pile. Total time consumption included 0.7 hours/pile of driving time assuming the distance of 40km/pile, while measuring was estimated at 0.5 hours/pile.

METHODS

Effective time and productivity with analysis

Through time studies in papers II and III, effective time and productivity of cutting methods were established and applied to determine harvesting costs of cutting methods used within both studies. Total effective time was based on the time consumptions identified from work elements of the continuous time study, which included: Moving; boom-out, felling, delimbing, cross cutting, and collecting; Separating timber fractions; Miscellaneous time; and delays. When calculating effective time consumptions, work elements were further classified into stem processing time, moving time, and miscellaneous time elements of which, the aggregate time provided the total effective time, as displayed in Equation 1. Stem processing times were modeled as a function the stem size (DBH) of removal varying between 5-17 cm, moving times were modeled as a function of removal (trees/ha), while miscellaneous time was determined by dividing the total miscellaneous time by the number of stem processing within each of the cutting methods (paper III) and an average of the cutting methods in paper II. To determine the effective productivity, the total effective times classified by stem size (DBH) of removal, were converted into a productive volume per hour measured as the productive machine hour (m^3/PMH_0), excluding delays (Equation 2).

$$TEc = PTc + Mc + MS \tag{1}$$

where *TE* = total effective time (seconds/stem), *PT* = stem processing time (seconds/stem) and *M* = moving time (seconds/stem) for cutting method *c*; *MS* = miscellaneous time.

$$Pc = \frac{(3600\ )}{(TEc*1000/Vc)} \qquad (2)$$

where *Pc* = effective productivity (m^3/PMH_0), *TEc* = total effective time (seconds/stem) and *Vc* = volume of removal (dm^3/tree) for cutting method *c*.

Operative productivities (m^3/PMH_{15}), including delay times < 15 minutes were determined by dividing measured effective productivities (m^3/PMH_0) by a previously estimated coefficient (1.393) utilized to convert effective productivity into an operative productivity within thinning operations, as utilized by Kärhä et al. (2004) and displayed in Equation 3.

$$POc = PEc*D \qquad (3)$$

where *POc* = opperative productivity (m^3/PMH_{15}) and *PEc* = effective productivity (m^3/PMH_0) for cutting method *c*; *D* = delay coefficient (delay times shorter than 15 minutes).

Operative productivities of cutting methods were estimated at stem sizes (DBH) of removals between 5-17 cm. Regression analyses using SPSS v. 20 statistical software were performed on each cutting method to ascertain productivity functions utilized in determining cutting costs (Paper II). Within papers II and III, statistical analysis of stem processing times, moving times, and productivities were determined through one-way analysis of variance (ANOVA) tests to determine differences between cutting methods.

Crane scale accuracy and analysis

Accuracy of crane scale measurement was determined in paper IV, where the truck and trailer and forwarder monitoring tests observations were utilized to determine accuracy of the measured weights following recommended crane scale calibration and adjustment guidelines (Metsäteho 2011). Accuracy calculations, as measured by the percent difference of timber truck and trailer scale were determined as the percentage share of the measured difference between the loader scale weight (kg) and weigh bridge weight (kg) divided by the weigh bridge weight (kg).

Measured accuracy of timber truck and trailers is determined by Equation 4, as shown in paper IV and derived from loader scale calibration and adjustment guidelines (Metsäteho 2011):

$$Td = \frac{(LSt - Wb)}{Wb}*100 \qquad (4)$$

where *Td* = timber truck difference (%), *LSt* = timber truck loader scale weight (kg), and *Wb* = weigh bridge weight (kg).

Accuracy calculations within forwarder monitoring of test weightings, as measured by the percent difference were derived as a percentage from the difference between the loader scale weight (kg) and the control weight (kg) multiplied by the number of repeated lifts and divided by the sum of the control weight (kg) multiplied by the number of repeated lifts.

Measured accuracy of forwarder crane scale during monitoring check were based on the loader scale calibration and adjustment guidelines (Metsäteho 2011) and is determined by Equation 5, as displayed in paper IV:

$$Fd = \frac{(LSf - (Cw * Nl))}{(Cw * Nl)} * 100 \qquad (5)$$

where *Fd* = forwarder difference (%), *LSf* = forwarder loader scale weight (kg), *Cw* = control weight (kg), and *Nl* = number of repeated lifts.

Comparisons of the accuracy results were determined by the average differences and their standard deviations of the measured variables within each category, while comparison of the accuracy results against standards for compliance, requiring accuracy within ± 4% difference (Ministry of Agriculture and Forestry 2008b) were conducted by identifying the percentage share of observations within a ± 4% difference. To identify possible statistical differences among the categories within the specified variable, statistical analyses with SPSS v. 20 statistical software was conducted. A one-way analysis of variance (ANOVA) was performed to identify any statistical differences among scale manufacturers and quarters with a post hoc test selected to account for unequal variances and sample sizes of the categories, while independent samples Welch's t-tests were utilized to measure statistical differences of the reported accuracies by measuring principle, timber assortments, and contractors. Additionally, regression analyses were performed on the absolute mean accuracies of observations classified by loader scale weight to identify correlations between average accuracy and loader scale weight classifications.

Supply chain costs and profitability

Costs of performing operations in small-diameter forest stands were calculated by examining the total harvesting costs (papers II and III), total supply chain costs (papers I and III), and measuring system costs (paper IV) within the papers contributing to this study. Additionally, profitability was examined in papers I and III.

Harvesting costs in papers II and III were determined by the aggregate cost of cutting and forwarding operations. Cutting costs, based on the stem size (DBH) of removal, were determined by dividing estimated machine operating cost by the operative productivity (m^3/PMH_{15}) derived from the effective productivity (m^3/PMH_0) of the cutting methods from Equation 2 and adjusted into an operative productivity. Forwarding costs were estimated with cost functions as a function of removals (m^3/ha) derived from forwarding time consumption models of Kärhä et al. (2006) and estimated machine operating costs within the study.

Total supply chain costs from harvesting to delivery at the gate of energy plants and pulp mills were determined in papers I and III. Total supply chain costs were calculated as the aggregate costs of the components of the supply chain, which included: Stumpage price, cutting cost, forwarding cost, comminution cost, storage cost, road transportation cost, and overhead cost. Variation in supply chains was accounted for by the different supply chains utilized within papers I and III. Within paper I, the whole-tree harvesting of energy wood was performed utilizing roadside chipping. Total supply chain costs of paper III utilized the integrated production of pulpwood and delimbed stemwood with supply chains split between roadside chipping and chipping at plant. Measuring system costs were determined in paper IV, by the estimated operating costs of a crane scale system and the manual timber pile measurement system divided by the estimated time consumption of measurement operations on three separate working volumes in a year.

System profitability was determined by two methods in paper I and III: 1). Examining total production costs dependent on stem size (DBH) of removals against raw material market prices minus the allocation of real and variable levels of subsidies provided under the Kemera incentive system (paper I); 2). Determining the gross profit margins associated with different harvesting systems under roadside chipping and chipping at plant supply chains. Gross profit margin was determined by dividing gross income with and without allocated PETU incentives (revenue – total supply chain costs) by their calculated revenues and was represented as a percentage share (paper III).

RESULTS

Harvesting technologies and operation methods

Harvesting technologies and operation methods utilized within papers II and III to a large degree, focused on the utilization of multi-tree handling technology, delimbed stemwood recovery, and reduction of timber assortments as a means to increase productivity and reduce costs.

Utilization of multi-tree handling occurred in five of the six cutting methods in paper II varying from 64-83%. Within paper III, MTH was utilized in four of the six cutting methods with utilization varying between 17-74%. The variation of processed stems utilizing multi-tree handling was between 1-5 stems per handling with an average bunch size of 1.77 stems in paper II, while within paper III the variation of processed stems was slightly higher at 1-7 stems per handling with an average bunch size of 1.4 stems. Average bunch sizes were found to be highest within the delimbed stemwood cutting methods utilizing separate fractions at 2.1 stems (paper II) and 1.9 stems per bunch (paper III). Within the time studies, stem processing times were found to be statistically significant ($p \leq .05$) when dependent of the stem size (DBH) of removals varying between 5- 17 cm and by cutting methods utilized within the studies of paper II and III. Processing times by cutting methods varied due to the cutting method, when assuming reasonable comparability based on standard deviations of the average volume of removal and average stem size of removal. Time consumption of the pulpwood cutting methods utilizing MTH were 3-8% higher (paper II) and 2-19% lower (paper III) than that of pulpwood applying single-tree handling. Integrated cutting methods were approximately at the same level as the pulpwood MTH method in paper II. With DBH of removals between 5-17 cm, the integrated (10 cm) method and delimbed stemwood method with combined fractions were found to have processing times 4-10% higher per handled stem than that of the pulpwood STH method (paper II). Within paper III the integrated cutting time consumption were found to be 14-15% higher than the pulpwood STH method and held the highest time consumption of the methods analyzed. Of the delimbed stemwood methods, combining fractions reduced processing time consumption by 1-8% (paper II) and approximately 9-11% (paper III) at a DBH of removal of 5-17 cm. The delimbed stemwood method with combined fractions was found to have the lowest processing time within paper III of the integrated and delimbed stemwood methods analyzed and was 9-14% lower than the pulpwood method employing single-tree handling.

Large variations in productivities were found to exist between integrated and delimbed stemwood cutting methods when compared to the cutting of pulpwood, combined and separate fractions, and by the stem size (DBH) of removal. Relative differences in effective productivities are displayed through selected cutting methods of paper II and III (cf. Figure 1-2). Within paper II, productivities varied between 3.2-27.9 m^3/PMH_0 (2.4-20.1 m^3/PMH_{15}), while productivities were found to vary from 2.0-25.8 m^3/PMH_0 (2.8-35.9 m^3/PMH_{15}) in paper III. Large differences in productivities of pulpwood and the combined integrated and delimbed stemwood methods were found to occur when stem size of removal (DBH) was below 11 cm. Decreasing the stem size (DBH) of removal, productivities were found to increase when compared to pulpwood utilizing single-tree handling with productivities of integrated and delimbed stemwood increasing from 4-121% (paper II) and up to 168% (paper III) greater than pulpwood (STH) with decreases in stem sizes from 15 cm to 7 cm. When comparing productivities of the pulpwood methods, the pulpwood MTH method was found to have productivities varying from 2% higher to 7% lower (paper II) and 11-25% higher (paper III) than that of the pulpwood method utilizing STH.

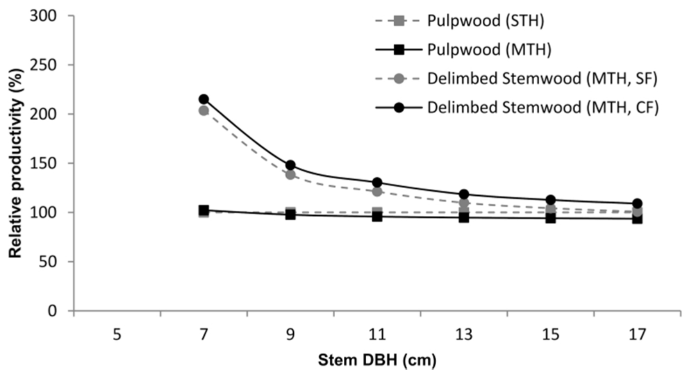

Figure 2. Relative productivity differences established when analyzing selected pulpwood and delimbed stemwood methods (paper II).

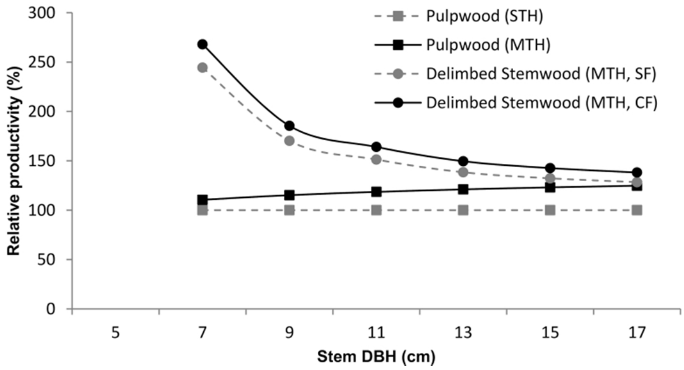

Figure 3. Relative productivity differences established when analyzing selected pulpwood and delimbed stemwood methods (paper III).

Comparing the effect of MTH on delimbed stemwood methods in paper III, increases in productivity from 3-14% were identified when examining the delimbed stemwood methods (MTH) and (STH) with combined fractions. Utilizing combined fractions instead of separate fractions when harvesting delimbed stemwood was also found to increase productivities by 1-8% (paper II) and 8-11% (paper III), especially in smaller stem sizes, where stem size (DBH) of removal varied between 5-17 cm. Differences in harvesting costs, comprised of cutting and forwarding costs, attributed to increased productivities through utilization of multi-tree handling, delimbed stemwood removal in integrated and delimbed stemwood cutting methods, and decreasing the number of timber fractions. Additionally, harvesting costs were modeled as a function of stem size and reliant on the stated removals of energy wood and pulpwood fractions utilized in papers II and III. Cutting costs of the selected methods varied between 3.6-30.0 $\$/m^3$ (2.8-23.1 €/m^3 (assuming: 1USD:0.77 EUR)) in paper II and 2.6-33.4 €/m^3 within paper III based on stem size (DBH) of removals between 5-17 cm. Forwarding costs accounted for a smaller cost share comparatively and were between 4.7-5.3 $\$/m^3$ (3.6-4.1 €/m^3 (assuming: 1USD:0.77 EUR)) (paper II) and 6.1-6.8 €/m^3 in paper III.

When examining the ability of harvesting systems to reduce costs, multi-tree handling of pulpwood compared to single-tree cutting of pulpwood was found to account for a reduction in harvesting costs by 1.5% at a DBH of removal at 7 cm, while increasing harvesting costs by up to 3.4% at 17 cm (paper II). Within paper III, pulpwood harvesting utilizing multi-tree handling was found to reduce harvesting costs by approximately 7.4-9.3% when compared to the single-tree handling method at a DBH of removal between 7-17 cm. The largest reductions in harvesting costs when compared to pulpwood harvesting with single-tree harvesting were found to occur when utilizing integrated and delimbed stemwood harvesting methods with reductions in costs from 0.1-44.0% (paper II) and 8.7-52.4% in paper III with the stem size (DBH) of removal varying between 7-17 cm. Within paper III, the delimbed stemwood method with combined fractions and MTH displayed harvesting costs 0.8-10.1% lower than that of the same method utilizing STH. Further reductions were identified when combining timber assortments within the same fraction, rather than separately. At a stem size (DBH) of removal between 5-17 cm, combining fractions attributed to reductions in harvesting costs from 1.5-4.3% (paper II) and 2.2-8.2% (paper III).

Accuracy and economic importance of crane scale measurement

Crane scale measurement accuracy and the cost implications of utilizing a crane scale measurement system were addressed in paper IV with the focus of determining accuracy and costs of crane scaling systems utilized in timber trucks and trailers, as well as forwarders utilized in timber procurement within Finland. When determining accuracy of timber truck and trailers and the forwarder crane scales through equations (1) and (2), forwarder crane scale accuracy was found to be higher than that of timber truck and trailer loader scales through the study (paper IV). The higher accuracy was, however, attributed to the difference between crane scales utilized in an operational environment, as the timber truck and trailer data compared to a controlled environment as the forwarding accuracy monitoring tests were.

Calculated accuracies based on the whole data sets were performed. The timber truck and trailer loader scale data displayed a negative average difference of -0.04% and a standard deviation of 4.27% with approximately 81.4% of the observations falling within the recommended ± 4% average difference limit, while 96.7% of the observations fell within an accuracy of ± 10%. Forwarder loader scales displayed an average difference of 0.02% with a standard deviation of 1.43% and found 99.2% of recorded observation accuracies within ± 4% and 99.8% within ± 10 %.

Crane scale weight classifications identified within the study were found to have a statistically significant ($p \leq .05$) effect on average errors when comparing crane scale weights in timber truck and trailers of < 10,000 kg and 10,000 - 30,000 kg ($p = .016$). When expanding weight classifications to increments of 5,000 kg in timber truck and trailer and 1,000 kg increments in forwarder observations, correlations were found to exist between accuracy measured by the average difference and loader scale weight classifications; Regression analysis on absolute mean accuracies by crane scale weights identified strong correlations (R^2= .87) for truck and trailer data and forwarder data (R^2 = .82). In comparing absolute mean accuracies and standard deviations with increases in loader scale weight, increases in average accuracy and decreases in their standard deviations were found to occur. When loader scale weights of timber truck and trailer observations varied between < 5,000 to 45,000-50,000 kg standard deviations of the average differences were found to vary between 2.97-5.66%, while standard deviations of average differences of forwarder loader scales with weight classifications from < 6,000-> 11,000 kg were found to vary from 1.48-4.08%.

When measuring accuracy by scale manufacturers, statistical differences ($p \leq .05$) among average differences of scale manufacturers occurred for both timber truck and trailer scale manufacturers and forward scale manufacturers utilized within the study. However, differences were relatively small with average differences varying from -0.04-0.24% and standard deviations of 2.75-3.66% for timber truck and trailer crane scale manufacturers and average differences of -0.41-0.34% and standard deviations of 1.03-2.59% among forwarder scale manufacturers. When measuring performance among the scale manufacturers, approximately ≥ 87% of observations among the five timber truck and trailer scale model observations had accuracies within the ± 4% required accuracy limit. Of the six forwarder crane scales utilized, ≥ 97% of observations fell within the specified accuracy range.

Among the crane scales utilized within the study, hydraulic measuring and strain gauge measuring principles were utilized. Crane scale manufacturers utilizing hydraulic pressure as the measuring principle were found to have lower absolute means and standard deviations than that of the scales utilizing strain gauge measuring (Paper IV). Statistically significant average differences were identified when comparing measuring principles utilized among forwarder crane scales (p = .000), while significant differences were not established among timber truck and trailer measuring principles (p = .163), where only one manufacturer utilized the strain gauge measuring principle. Average differences of approximately 87% of the strain gauge and 88.4% of the hydraulic pressure measuring principles of the truck and trailer scale manufacturers were within the ± 4% accuracy limit, while 99% of strain gauge and 99.3% of the scales utilizing hydraulic pressure among the forwarder data fell within the ± 4% average difference.

Examining accuracy by time period, separating accuracy measurements into quarterly time periods found higher standard deviations and absolute means occurred in both timber truck and trailer and forwarder data sets during the second quarter. Average differences of timber truck and trailer data varied from -0.33-0.18%, while standard deviations from 3.84-4.71%. Approximately 77.5-85.3% of accuracy measurements between Q1 and Q4 fell within ± 4%. Within the forwarder measurement accuracy data average differences among the quarter’s ranged between -0.09-0.19% and standard deviations from 1.17-1.74%. Between 98.5-100% of the forwarder accuracy measurements, when segmented by quarterly time periods were found to be within ± 4%. Calculated average differences among quarterly measurements were found to be statistically significant for both truck and trailer (p = .000) and forwarder (p = .006) observations with significant differences occurring among Q1 and Q2 and between Q1 and Q4 within the forwarder data and among all quarters measured with the truck and trailer data.

Accuracy of measurements when compared among pulpwood and logwood timber assortments within the truck and trailer data found average differences of the assortments to display a statistically significant difference (p = .000). Pulpwood assortments displayed an average difference of approximately 0% and a standard deviation of 4.23%, while the logwood measurements displayed an average difference of -0.44% and standard deviation of 4.64%. A slightly larger percentage of pulpwood observations were within the required ± 4% accuracy limit at 81.6% compared to 79.3% of logwood observations. Additionally, when measuring performance of contractors within both studies, contactor accuracies were found to be statistically different (p = .032). However, both sets of contractors utilized in the forwarder and timber truck and trailer data displayed high absolute mean accuracies with > 90% of truck and trailer contractors ≤ 4% and 99.4% of forwarder contractors displaying mean accuracies of ≤ 4%. When examining system costs of operating a crane scale measurement system compared to a manual timber pile measurement system, the unit costs of a manual timber pile measurement system were 18.2-45.5% higher than that of the crane scale measuring system when working volumes varied from 20,000 m^3 to 30,000 m^3. Lower unit costs allowed the crane scale measurement system to reduce costs by approximately 1,200-4,500 €/year with estimated working volumes varying between 20,000 m^3 to 30,000 m^3 when compared to the traditional manual timber pile measurement within the study.

Integrated energy wood and pulpwood supply chain considerations

To examine the effect of harvesting systems on total operating costs, integrated energy wood and pulpwood supply chains utilizing roadside chipping and chipping at plant chain of supplies were compared (paper III). An operation area of 3 ha, average wood chip and pulpwood transportation distances in Finland of 70 km for wood chips (energy wood chips and delimbed stemwood) and 110 km for pulpwood (Strandström 2012), pulpwood market prices of 39 €/m^3 and 37.2 €/m^3 (18.6 €/m^3), and removal volumes were assumed in paper III. Sole production of pulpwood with single and multi-tree handling operating systems produced total supply chain costs varying from 34.5-55.9 €/m^3 with a stem size (DBH) of removal between 7-17 cm. Total costs of the production system utilizing multi-tree handling were approximately 2-6% lower than with the method utilizing single-tree handling and can be attributed to the increases in harvesting productivity with multi-tree handling. When looking at the Integrated and delimbed stemwood harvesting methods utilized within a roadside chipping supply chain, total supply chain costs were found to vary between 33.7-55.3 €/m^3 with a stem DBH varying between 5-17 cm. When comparing integrated and delimbed stemwood harvesting methods to the pulpwood harvesting method with single tree handling, total supply chain costs when utilizing roadside chipping were between 1-28% lower than the pulpwood (STH) operating method at a stem size (DBH) of removal between 7-11 cm. The delimbed stemwood method utilizing multi-tree handling and combined fractions was found to have approximately 0.5-5.1% lower operating costs when compared to the same delimbed stemwood method, but with separate fractions and held the lowest total supply chain costs varying from 33.7-37.3 €/m^3. By conducting operations with chipping performed at the plant, rather than at roadside, total operational costs of integrated and delimbed stemwood harvesting methods were able to be reduced by a further 2-11% at a stem size (DBH) of removal between 5-17 cm with total operational costs varying between 32.5-49.8 €/m^3.

Cost shares of the supply chain elements at a stem size (DBH) of removal at 11 cm were identified within the study. Harvesting costs, the combined costs of cutting and forwarding, were found to be the largest cost factor within both roadside chipping and chipping at plant supply chains. Harvesting costs varied due to harvesting system in use with the pulpwood harvesting systems (STH and MTH) accounting for 43% to 41% of supply chain costs, respectively. Within the roadside chipping supply chain, integrated and delimbed stemwood harvesting costs were approximately 31.9-38.1% of total costs, while when chipping at plant harvesting costs accounted for 37.2-40.0%. The second largest cost factor identified in both supply chains were transportation costs, which varied between 21-29% of total costs.

Gross profit margins, based on each of the cutting systems were calculated as a percentage share by dividing gross income by assumed revenues based on removals (paper III). For the roadside chipping supply chain, gross profit margins varied from -48.5-12.8% at stem sizes (DBH) of removal between 5-17 cm. Profitability of systems were highly dependent on stem sizes. When operating at stem sizes of > 11 cm, the sole production of pulpwood utilizing multi-tree handling was found to be the most profitable with profit margins between 8.6-11.5%. Operating in stem sizes below 11 cm, the delimbed stemwood method with multi-tree handling and combined fractions was the most profitable production system with gross profit margins vary from -36% to as high as 12.8% in stem sizes (DBH) of removal of 7-11 cm and was the only energy wood and pulpwood production system to be profitable at a stem size (DBH) of 7 cm. By comparison, at a stem size of 7 cm, the production of pulpwood utilizing the pulpwood (MTH) method had a negative gross profit margin (loss) of -35.2% compared to a 2.5% gross profit when producing energy wood and pulpwood utilizing the delimbed stemwood (MTH, CF) method, representing a profit margin difference of 32.7%.

Profitability, based on profit margins, increased further when the chipping at plant supply chain was utilized instead of roadside chipping. Profit margins varied from -43.4-15.7%. The delimbed stemwood method (MTH, CF) was found to have higher profitability levels in a wider variation of stem sizes (DBH) between 7-15 cm with profit margins varying between 8.7-10.3%. In stem sizes (DBH) > 15 cm, the pulpwood (MTH) method was found to be the most profitable system to operate with a gross profit margin of approximately 8.6-9.9%. When comparing the profitability at a stem size (DBH) of 7 cm, the delimbed stemwood (MTH, CF) displayed a 26.5% difference in gross profit margin when compared to the Pulpwood (MTH) system. Profitability of the two supply chains analyzed, as well as the relative divergence in profit margins based on stem size (DBH) of removals for the pulpwood (MTH), integrated, and delimbed stemwood (MTH, CF) methods within paper III is represented in Figure 4.

Policy implications in relation to supply chain profitability

Financial incentives when operating in small-diameter forest stands for the production of forest chips to be utilized in combined heat and power were assessed in papers I and III. Effects of subsidies, as can be expected, lowered total operational costs and increased profitability. However, profitability levels were determined based on stem size of removals, market prices, and variable levels of incentives adding insight into under what conditions incentives may be needed. Within paper I, the aggregate production costs of a roadside chipping supply chain utilizing a whole-tree energy wood harvesting system were determined. Supply chain costs were between 41-47 €/m^3 (20.4-23.3 €/MWh), while the average price of forest chips was approximately 18 €/MWh. Low paying capability compared to the total operational costs determined based on forest stand and supply chain assumptions (paper I) suggested the inability of operating profitable whole-tree harvesting energy wood operations in small-diameter forest stands < 80 dm^3 without the aid of financial incentives. When including applicable incentives through the Kemera subsidy system (paper I), total production costs were found to be lower than the assumed market price of energy wood chips when operating in small-diameter forest stands > ~ 20 dm^3.

Additionally, scenarios where decreases in allocated subsidies were tested to determine energy wood profitability under market conditions reflected in forest chip prices of 15 €/MWh, 17.5 €/MWh, and 20 €/MWh and the potential change in allocation of incentives by decreases in subsidies were examined. Assuming utilization of the Kemera subsidies, profitable operations were found to occur at minimum average stem sizes of 47-17 dm^3 with forest chip prices paid at the gate of plants varying between 15-20 €/MWh, displaying the effect market prices have on viability of energy wood operations. When reducing allocations of subsides, from 25% below the subsidy levels assumed, profitability was found to occur with an average stem size of 40 dm^3 at a forest chip price of 17.5 €/MWh. A reduction of subsidies of 50% found operations to be profitable with a minimum average stem size of 35 dm^3 at forest chip prices of 20 €/MWh. Results indicated that based the subsidy levels provided through the kemera subsidy system, reductions in financial incentives by approximately 25-50% depending on market prices of forest chips would be possible.

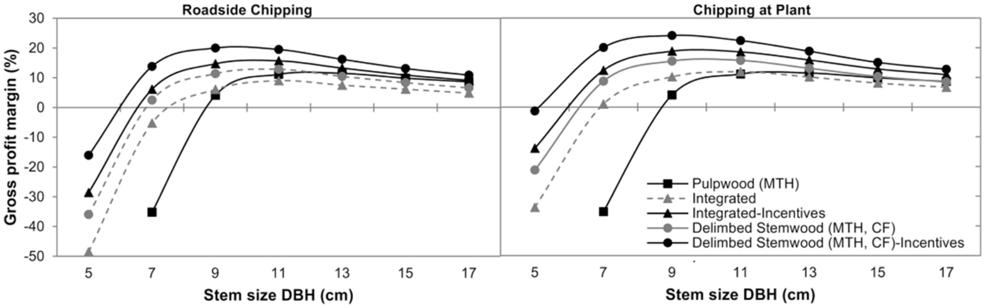

Figure 4. Gross profit margin by supply chain and selected cutting methods with and without applicable incentives as a function of stem size (DBH) of removal (paper III).

Following a reorganization of the subsidies offered for combined heat and power production from energy wood to be adopted in 2015, available subsidies (paper III) are approximately 42.5% lower than previously assumed in paper I. The effects of subsidies on integrated energy wood, delimbed stemwood and pulpwood production were examined through a roadside chipping and a chipping at plant supply chain in paper III. The relative divergence in profit margins by selected harvesting methods and supply chains performed with and without applied incentives in paper III is elucidated in Figure 4. Profitability levels without subsidies were generally distinguished at stem size (DBH) > 7 cm for integrated and delimbed stemwood harvesting methods when chipping at roadside.

With lower total costs, the profitability levels of integrated and delimbed stemwood methods when chipping at plant were approximately ≥ 7 cm. Increases in gross profit margins from 3.8-19.9% were found to occur when adding available financial incentives estimated to be offered within the PETU subsidy system at stem sizes (DBH) or removal from 5-17 cm. With the increase in gross profit margins, of the integrated and delimbed stemwood harvesting methods analyzed, profitability limits would occur at a decreased stem size (DBH) of removal between 5-7 cm.

DISCUSSION AND CONCLUSIONS

Efficiency improvements and cost reductions through rationalization

By collectively utilizing findings from papers I-IV, means or pathways to increase efficiency, reliability, and reduce supply chain costs when harvesting small-diameter forest stands for the production of energy were identified. Rationalization of harvesting technologies and methods, timber measuring technology, and policy through the application of financial incentives was found to increase efficiency and reduce costs. When combined or utilized individually, the various rationalization methods to increase efficiency, reliability, and reduce cost were able to increase the viability of production of energy wood from small-diameter stands that are prone to high costs and low profitability.

One of the critical areas where efficiency improvements and cost reductions occurred was within cutting, where the cutting systems and cutting methods employed had robust effects on the productivity of stem processing, leading to variation in cutting costs based on the harvesting system employed. Within the productivity and cost studies (paper II and III), time studies were conducted on harvesting plots within one forest stand utilizing one machine unit and one operator for each study and were assumed to be reasonably comparable, which potentially introduced bias into the study. Comparability of the time and productivities of the cutting methods strived to compare methods under similar plot conditions within the same forest stand conditions. However, variation in distribution of removals was apparent among the methods due to material requirements between the methods. Furthermore, within paper II and III, correlation between stem size (DBH) of removals provided larger variations than expected. Low correlations potentially suggest other influencing factors, such as tree species, or the operator influencing processing times and productivities established. However, notice should be given that depending on the machine operator large variations in productivity as great as 35-40% have been found to occur when the same machine is utilized by different operators as previously displayed by Sirén (1998), Kärhä et al. (2004), and Ovaskainen (2009). Additionally, as Harstela (1993) notes, absolute productivity requires collection of operating data from not just one operator, but many to determine reliable average productivity. Both time and productivity studies (paper II and III) were found to be conducted with reasonable study data when compared to previous cutting time studies of Kärhä et al. (2004), Kärhä and Mutikainen (2008), Iwarsson Wide and Belbo (2009), Di Fulvio et al. (2011), Kärhä (2011b), and Lehtimäki and Nurmi (2011). To compare the results of the productivities achieved during cutting, productivities of the cutting systems utilized in papers II and III were compared to similar systems utilized in productivity studies in thinning stands with stem size of removal approximately 11 cm (volume of removal ~50 dm^3). Estimated productivities within paper II and III found productivities of pulpwood cutting utilizing single-tree handling to be approximately 10.5 m^3/PMH_0 (7.5 m^3/PMH_{15}) (paper II) and 7.3 m^3/PMH_0 (10.1 m^3/PMH_{15}) (paper III), while estimated productivities under similar first thinning conditions within Finland of Kärhä et al. (2004) and Lehtimäki and Nurmi (2011) were found to be lower at 5.6 m^3/PMH_{15} and 6.1 m^3/PMH_0, respectively.

As a comparison, productivities of other studies with integrated and delimbed stemwood cutting methods utilizing multi-tree handling under similar conditions were examined. Productivities were found to be approximately ≥ 27.4% of the compared pulpwood cutting productivities with single-tree handling capabilities with recent integrated and delimbed stemwood studies having estimated productivities of 8.4-9.3 m^3/PMH_0 (Lehtimäki and Nurmi 2011) and 10.7 m^3/PMH_{15} (Kärhä 2011b). Of the productivities established within the papers utilized for this study, both integrated and delimbed stemwood cutting methods at a stem size (DBH) of removal of 11 cm were found to be approximately 12.7-13.7 m^3/PMH_0 (9-9.8 m^3/PMH_{15}) (paper II) and 9.5-11.9 m^3/PMH_0 (13.3-16.6 m^3/PMH_{15}) (paper III) representing increases in productivities of ≥ 16.7% (paper II) and ≥ 24% (paper III) when compared to the pulpwood productivities (STH) established in both studies. Increases in productivities were found to be of similar and reasonable proportions when compared to those of Kärhä et al. (2004), Lehtimäki and Nurmi (2011), and Kärhä (2011b). The relatively higher productivities achieved in paper III when compared with paper II, could be explained by the high proportion of birch within the harvesting plots of the study in addition to the operator and harvesting system, leading to higher productivities achieved in harvesting of broadleaf trees when compared to pine and spruce, due to the smaller proportion of crown biomass on the tree (Heikkilä et al. 2005).

Of the technologies and methods contributing to increasing efficiency and reducing costs, the utilization of multi-tree handling, implementation of integrated and delimbed stemwood recovery, and the reduction of timber assortments were identified as the largest contributors to cost reductions within the studies of paper II and III. Productivity of pulpwood cutting when using multi-tree handling was found to be from 2% higher to 7% below (paper II) that of the pulpwood method with STH. While within paper III 11-25% increases were identified by utilizing MTH (paper III). The effect of the operator, as noted in paper II, contributed to the small increase to decrease in productivity based on stem size (DBH) of removal occurring in paper II, and was attributed to the relative inexperience of the operator in certain cutting methods. However, when compared to the increase in productivity reported in paper III, findings were similar to those of Lilleberg (1994), Bergkvist (2003), and Gingras (2004), where the ability to process more than one stem at a time increases productivity of pulpwood cutting by an average of 20-30%, or a 30-40% increase when increasing processed stems per handling by 2-3 trees (Iwarsson Wide and Belbo 2009). However, increases in productivity by utilization of MTH were less pronounced when comparing delimbed stemwood methods (paper III) with increases of only 3-14% and were found to be lower than increases estimated by Lehtimäki and Nurmi (2011) and Iwarsson Wide and Belbo (2009).

Productivity increases identified when utilizing multi-tree handling technology in separate pulpwood harvesting were found to translate to decreases in costs from 7.4-9.3% with stem size (DBH) of removals varying between 7-17 cm compared to a traditional single-tree handling method for pulpwood harvesting (paper III). Decreases in costs were less pronounced when comparing similar methods in paper II, with a decrease in cost of 1.5% at a stem size (DBH) of 7 cm due to the machine operator's skill level with the harvesting technique. However, as noted in paper II, the higher harvesting costs can be attributed to low productivities derived from the relative inexperience of the operator with multi-tree handling in pulpwood thinnings. Through both studies, however, the ability of multi-tree handling technology in increasing productivity and reducing harvesting costs was apparent not only among the pulpwood methods analyzed (cf. Figure 2-4).

With the implementation of integrated and delimbed stemwood harvesting utilizing multi-tree handling, increases in recovery of both delimbed stemwood capable of being allocated to either energy wood or pulpwood fractions, allowed for increases in productivity and further reductions in costs, particularly in conditions with smaller stem size (DBH) of removals < 11 cm. When comparing integrated and delimbed stemwood harvesting methods to that of pulpwood utilizing single-tree handling, significant increases in cutting productivity occurred varying from 4-121% (paper II) and 8.6-168% (paper III) greater than the pulpwood (STH) cutting method based on stem size (DBH) of removals between 7-17 cm. The increases in productivity directly translated into reductions in total harvesting costs by up to 44% when utilizing the Integrated harvesting method (paper II) and as high as 52.4% with the delimbed stemwod method with combined fractions and MTH (paper III) when compared to pulpwood STH methods. The effect of MTH on harvesting costs however, was lower when comparing delimbed stemwood methods in paper III with reductions of costs varying from approximately 1-10% when compared to STH.

When determining profitable allocations of raw material under harvesting systems, both integrated and delimbed stemwood methods provide flexibility based on quality and material demands that allow the cutting method to adapt to needs based on market and quality requirements of energy facilities and pulp mills, as has been noted by Kärhä et al. (2011a). If high material requirements are present, energy wood and pulpwood assortments may be recovered separately, while when the pulp mill allows for lower quality material then delimbed stemwood harvesting methods allow for additional adaptability with lower stem sizes. As Jylhä (2011) has noted, the wood paying capability of pulp mills often restricts energy wood fractions to relatively low proportions when compared to pulpwood and has found harvesting of whole-trees from small-diameter forest stands to be unprofitable below pulpwood dimensions due to high harvesting costs. Integrated and delimbed stemwood harvesting, however, were able to increase productivity to a level where profitability based on total supply chain costs and wood paying capability of end use facilities occurred. Energy wood and pulpwood production was viable with proportions of energy wood fractions varying from 13-44% at a stem size (DBH) of removal increasing from 7-17 cm and when operating below 7 cm, the energy wood accounted for all removals (paper III).

However, profitability of the integrated and delimbed harvesting systems utilized were dependent on the assumed supply chains and transportation distances (paper III), which found total supply chain costs when chipping at plant approximately 2-11% lower than when chipping at roadside based on a stem size (DBH) of removal between 5-17 cm. Both supply chain scenarios were able to increase profitability over traditional pulpwood harvesting with dimensions considered to produce pulpwood (cf. Figure 4). Based on profit margins identified from pulpwood and roadside chipping supply chains, pulpwood production was found to be the most profitable when operating in stem sizes (DBH) greater than 11 cm, while with stem sizes between 7- 11 cm a delimbed stemwood system was identified as the most profitable (cf. Figure 4). Profitability, as measured by gross profit margin, when comminution occurred at the plant was further increased. Delimbed stemwood production was identified as the most profitable harvesting option and supply chain with stem size (DBH) of removals between 7-15 cm, while pulpwood production with multi-tree handling provided the highest profitability in stem sizes (DBH) greater than 15 cm (paper III). Results were found to confirm that delimbed stemwood harvesting, as suggested by Laitila et al. (2010), is feasible in stem sizes (DBH) from 7-13 cm and is certainly an economically viable option in the production of energy wood and pulpwood.

An additional method to improve efficiency of harvesting within small-diameter forest stands was found to be adapting harvesting and sorting methods to combine timber fractions and thereby reduce the number of assortments handled. Increases in productivity were found to be between approximately 1.8-8.2% (paper II) and 8-11% (paper III) when utilizing combined fractions compared to separate fractions within a delimbed stemwood harvesting system. Increases in productivities were found to be higher than suggested by Brunberg and Arlinger (2001), where cutting productivity could be increased by 1% when decreasing each assortment number. Increases in productivity when utilizing combined assortments were found to reduce cutting costs from 1.5-4.3% (paper II) and 2.2-8.2% (paper III) at stem size of removals between 5-17 cm.

Technology utilization within timber measurement has also been an area where rationalization of small-diameter forest can occur and in turn increase reliability and reduce costs. With increased focus on efficiency, reliability, and cost reductions within logistics, crane scale measuring has increased its share in timber measuring throughout Finland (Melkas and Hämäläinen 2012), particularly after becoming an official measuring method for industrial roundwood in 2009 (Ministry of Agriculture and Forestry 2008b, 2010) and agreement between interested parties within the forest and energy industries concerning energy wood measurement (Lindblad et al. 2010). Furthermore, utilization of crane scale measurement has been viewed as a technical solution to increase efficiency and reduce costs within timber procurement, especially in small-diameter forest stands (Oikari et al. 2010). Crane scale measurement, in particular is an asset when utilized within integrated pulpwood and energy wood harvesting activities, due to the ability to handle both fractions (Kärhä et al. 2011a). When determining crane scale measurement accuracy, it was found that the large majority of accuracy measurements in both forwarder (99.2 %) and truck and trailer (81.4 %) data complied with accuracy requirements of ± 4 % set by the Ministry of Agriculture and Forestry in Finland (paper IV). The accuracies measured within the study (paper IV) displayed improved performance when compared to studies of Heikkilä et al. (2004) when determining accuracy by volume measurements and comparative descriptive statistics of crane scale measurements recorded in studies of Heikkilä et al. (2004), Hujo (2006) and Iwarsson Wide and Jönsson (2012).

Estimates of the percentage share of observations within accuracy limits were significantly higher compared to the estimated 41% of loader scale and 28% of timber pile measurement observations of Heikkilä et al. (2004) within the ± 4% accuracy limit, although accuracy by volume measurement was conducted with medium to small load sizes and storage piles. While when comparing accuracy by loader scale weight classifications, correlations between accuracy and weight (kg) were identified (paper IV) similar to the correlation between volume (m^3) and accuracy identified by Heikkilä et al. (2004). Additionally, comparative scale performance in paper IV was identified when comparing scale manufacturers utilizing similar test weight and weigh bridge accuracy calculations performed by Iwarsson Wide and Jönsson (2012). However, differences in suggested performance of hydraulic and strain gauge measuring principles occurred (paper IV). Within the crane scale study (paper IV), the largest variations in accuracies were determined to occur when observations were categorized by weight classification and seasonal time periods and suggested that accuracy is primarily dependent on the two. However, their percentage share of observations meeting accuracy requirements was still relatively high with > 70% of truck and trailer and > 98% of observations within ± 4% (paper IV). To further assess crane scale measuring as a means to increase efficiency, system costs were compared against a manual timber pile system (paper IV), finding that utilization of a crane scaling system has the potential to provide measurement cost reductions by approximately 18.2-45.5% when compared to the manual timber pile measurement system at the roadside when assuming volumes from 20,000-30,000 m^3 per year. The findings in cost reductions translated to cost savings of 1,200-4,500 €/year depending on working volumes when utilizing the crane scale system. Findings suggested that utilization of the crane scale system would increase cost efficiency in addition to providing a reliable measuring system to be utilized in timber procurement of not only industrial roundwood, but also energy wood.

Financial incentives were investigated as a final means to reduce operational costs when producing energy wood from small-diameter forest stands. Reductions of costs, however, were not derived from efficiency improvements, but through the effective use of policy. With the goal of encouraging energy production from energy wood derived from small-diameter forest stands in Finland, financial incentives have in the past been provided through the Sustainable Silviculture Foundation Law (Kemera) and are estimated be allocated under the PETU system starting in 2015. Within paper I, applicable financial subsidies under the Kemera system were identified and applied to supply chain costs of a whole-tree energy wood harvesting system, which were found not to be an economically viable option when harvesting in typical small-diameter forest stands. When operating without the applicable incentives, it was found that the average stem size would need to be approximately 80 dm^3 with market prices of energy wood chips at 18 €/MWh to become financially viable (paper I), which has been similar to findings of Kärhä (2002), Vasara (2006), and Helynen et al. (2007). Furthermore, energy wood harvesting even when utilizing the subsidies has been found to be cost prohibitive, as noted by Laitila et al. (2010) with stem size (DBH) of removal of 8 cm in both whole-tree and delimbed stemwood harvesting systems utilizing a roadside chipping supply chain. Within the study of Laitila et al. (2010), the subsidized procurement costs of whole-trees were found to be 23% above the utilized market price of forest chips, while with higher harvesting costs, delimbed stemwood was approximately 38% greater than the utilized forest chip price.

Within paper I, market prices were found to have a robust effect on the profitability limits for production of energy wood from whole-tree harvesting with the required average stem size decreasing from 50-20 dm^3 and when forest chip prices paid upon delivery varied from 15-20 €/MWh. Findings suggested that depending on market prices, reductions in subsidies up to 25-50% could occur depending on forest chip prices. When determining profitability of integrated and delimbed stemwood harvesting methods under the PETU subsidy system for the production of energy wood (paper III), cost shares of energy wood supply chains alone were not profitable at a stem size (DBH) of removal of 11 cm with the roadside chipping supply chain, however at the same stem size and when chipping at plant, system costs of energy wood fractions were below the estimated market price of 37.2 €/m^3 (18.6 €/MWh). However, when integrating both pulpwood and energy wood fractions with the proportion of energy wood removals varying from 13-44% at stem sizes (DBH) of 7-17 cm, integrated and delimbed stemwood harvesting methods were found to have break-even points at between 7-9 cm when chipping at roadside and > 5-7 cm when chipping at plant without the utilization of available subsidies.

When applying applicable incentives between € 808-933 based on paper III, profit margins were found to increase from 3.8-19.9% with the largest increases at stem sizes between 5- 7 cm, however low profit margins were still evident and operations at stem sizes (DBH) of ≤ 5 cm were still considered economically unviable. Utilization of incentives to increase the cost competitiveness of energy wood production in Finland in many cases have allowed for the production of energy wood from various stand conditions and harvesting systems that might not have otherwise occurred (Kärhä 2002; Vasara 2006; Helynen et al. 2007). While incentives provide an important tool in decreasing costs of energy production in small-diameter forest stands, they also play an important role of encouraging active management leading to improved silvicultural conditions without which, reduce growth rates and raw material quality would lead to reductions in value when producing future industrial roundwood (Varmola and Salminen 2004; Huuskonen and Hynynen 2006; Hilska-Aaltonen 2009). Identifying where and when subsidies allow for the production of energy wood among whole-tree, delimbed stemwood, and integrated harvesting systems provides an important means to identify efficient systems based on stand conditions, supply chains, and market conditions and should be encouraged.

Future research

Systemic factors influencing the profitability of energy wood production from small-diameter forest stands have been noted to include high harvesting costs particularly due to the small stem sizes and low removals per hectare. Rationalizing aspects of operations within energy wood supply chains through harvesting methods, technology, and utilization of policy have been found to be an effective way to mitigate high costs from performing operations in small-diameter forest stands. Laitila et al. (2010) have noted that intelligent selection of harvesting methods for different stand conditions allows for the minimizing of distances associated with transport and costs of harvesting. This rational can be further extended by focusing on methods and technology that can be utilized throughout the whole supply chain from forest to the gate of energy facility or pulp mill. Technologies and methods that are proven to increase efficiency and reduce costs, should be utilized whenever possible. Further research covering the influence of proportion of energy wood and pulpwood removals, payload influences on forwarders and trucks, and cutting methods which increase productivity should be actively researched to find further pathways to reduce costs within the often cost prohibitive environment of harvesting energy wood and industrial roundwood from small-diameter forest stands.

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