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Mechanized tree planting in Finland and improving its productivity

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Academic dissertation

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ABSTRACT

The demand for mechanized tree planting is expected to increase in the future. This dissertation assessed mechanized tree planting in Finland and suggests ways to improve its current productivity. The work on which this thesis is based was described in five peer-reviewed articles (I–V) addressing four specific research questions (SQs) that focus on productivity and cost-competitiveness, automation, capacity utilization, and the quality of planting work.

While productivity of mechanized planting is higher than manual methods, it is not yet cost-competitive. However, increasing efficiency by skilled operators and worksite selection make it possible for mechanized planting costs to remain lower than those of excavator spot mounding followed by manual planting. Increasing productivity and reducing operating costs are possible with an effective automatic seedling feeding system, although the Risutec APC is not yet sufficiently developed to reach that goal. Planting machine capacity is underutilized and could be utilized more effective to enhance productivity and cost-efficiency. Technical availability of planting machines in Finland is good, and the quality of mechanized planting work is high. Optimization and integration of the entire mechanized planting chain from the nursery to outplanting is important to minimize total cost.

In summary, for mechanized planting to be effective the following criteria must be satisfied: machine reliability; highly-skilled machine operator; suitable worksite; seedling quality, availability, and supply to worksite. In the future, it is important to continue developing new and existing machines to enhance productivity, e.g., by continuously working planting machines.

Keywords: Planting machine; mechanization; silviculture; regeneration; seedling

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Suonenjoki, April 2017

Tiina Laine

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following Articles, referred in the text by their Roman numerals (I–V). Articles (I–V) are reproduced with the kind permission of the publishers.

I **Laine T.**, Kärhä K., Hynönen A. (2016). A survey of the Finnish mechanized tree-planting industry in 2013 and its success factors. Silva Fennica vol. 50 no. 2 article id 1323. 14 p.
https://doi.org/10.14214/sf.1323

II Hallongren H., **Laine T.**, Rantala J., Saarinen V-M., Strandström M., Hämäläinen J., Poikel, A. (2014). Competitiveness of mechanized tree planting in Finland. Scandinavian Journal of Forest Research 29:2, 144–151.
https://doi.org/10.1080/02827581.2014.881542

III Rantala J., **Laine T.** (2010). Productivity of the M-Planter tree-planting device in practice. Silva Fennica vol 44 no. 5 article id 125: 859–869.
https://doi.org/10.14214/sf.125

IV **Laine T.**, Rantala, J. (2013). Mechanized tree planting with an excavator-mounted M-Planter planting device. International Journal of Forest Engineering 24:3, 183–193.
https://doi.org/10.1080/14942119.2013.844884

V **Laine T.**, Saarinen, V-M. (2014). Comparative study of the Risutec Automatic Plant Container (APC) and Bracke planting devices. Silva Fennica vol 48 no. 3 article id 1161. 16 p.
https://doi.org/10.14214/sf.1161

AUTHOR’S CONTRIBUTION

Article I
Analysis was based on report 233/2015 published by Metsäteho. Kärhä formulated the initial aim of the study and had the main responsibility for formulating the questions of the survey together with Hynönen, Laine and other co-authors of the Metsäteho report. Hynönen interviewed most of the planting machine contractors, Laine interviewed four contractors. Laine analyzed the data for the scientific article together with Kärhä and Hynönen and was responsible for writing and revising the article in collaboration with co-authors. The original report: “Koneellinen metsänistutus ja sen tehostaminen Suomessa” (Mechanized planting and improving its efficiency in Finland) is available in Finnish at: http://www.metsateho.fi/wp-content/uploads/2015/02/Raportti_233_Koneellinen_metsan-istutus_ja_sen_tehostaminen_kk_ym.pdf. Using the same data, Hynönen made his master’s thesis: “Koneistutuksen nykytila ja tulevaisuus Suomessa: Toimintamalli koneistutuksen laajentamiseen ja kehittämiseen” (Mechanized tree planting today and in the future in Finland: The way to expand and develop mechanized planting) and it is available in Finnish at: http://epublications.uef.fi/pub/urn_nbn_fi_uef-20141152/urn_nbn_fi_uef-20141152.pdf.

Article II
Analysis was based on report 218/2011 published by Metsäteho. Other co-authors were responsible for formulating study objectives, analyzing the data and writing the original Metsäteho report. Laine participated in writing the scientific article together with Hallongren and they worked together to revise the manuscript. The original report “Koneellisen istutuksen ja taimikonhoidon kilpailukyky” (The competitiveness of mechanized planting and pre-commercial thinning) is available in Finnish at: http://www.metsateho.fi/files/metsateho/Raportti_218_Koneellisen_istutuksen_ms_ym.pdf.

Article III
Laine was responsible for collecting the data and writing the first version of the manuscript. Rantala formulated the initial aim of the study, helped with data analysis, finished the manuscript, and contributed to subsequent revisions.

Article IV
Laine helped to formulate the specific objectives of the study, collected and analyzed all data, wrote the manuscript, and contributed to subsequent revisions. Rantala formulated the initial aim of the study, and helped interpret results and draw conclusions.

Article V
Laine had the main responsibility for research plan, data collection, analysis, interpretation and writing of the work described in the article. Saarinen was responsible for cost calculations and helped to draw conclusions.

TABLE OF CONTENTS

ABBREVIATIONS

AUT	An idealized planting device with automatic seedling feeding system
CONT	Continuous spot mounding
CSF	Critical success factor
DT	Disturbance time
FOA	Forest owners association
MA	Mechanical availability
MP	Manual planting
MU	Machine utilization
NIPF	Non-industrial private forest owner
NT	Non-worktime
NW	Non-workplace time
OP	Degree of operation
Pl	Seedling
PLANT1	Planting machine with one planting unit
PLANT2	Planting machine with two planting units
PT	Preparatory time
PWh	Productive work hour
REP	Degree of repair for the machine units
SFIE	A large silviculture and forest industry enterprise
SPOT	Spot mounding
SQ	Specific research question
ST	Service time
SW	Supportive worktime
TT	Total time
TU	Total utilization
WD	Work-related delay time
WP	Workplace time
WT	Worktime

1 INTRODUCTION

1.1 Reforestation in Finland

Soil preparation is a key task in the forest regeneration chain of Nordic forests, as it helps to guarantee an acceptable regeneration result together with proper seedling material. Soil preparation is needed to create favorable growing conditions for the next tree generation by e.g. improving the humidity and temperature conditions of the soil and reducing the risk of pine weevils (*Hylobius abietis* (L.)) and voles (e.g. Örlander et al. 1990; von der Gönna 1992; Örlander et al. 2002; Luoranen and Kiljunen 2006; Luoranen et al. 2007; Luoranen and Viiri 2012). Soil preparation has been mechanized for a long time (Sutton 1993; Strandström et al. 2009; Nilsson et al. 2010). Since 2000, mounding has become the most common soil preparation method in Finland, replacing disk trenching. The share of mounding as a soil preparation method has increased 224% from 2003 to 2013; meanwhile disc trenching has decreased 53% (Västilä 2004; Juntunen and Herrala-Ylinen 2014). Mounding is the most suitable soil preparation method when establishing Norway spruce (*Picea abies* (L.) Karst.) stands, and this partly accounts for spruce planting becoming more popular (Luoranen et al. 2007; Juntunen and Herrala-Ylinen 2014).

Mounding can be divided into ditch, inverting, and spot mounding. In spot mounding, a piece of soil, including the humus and mineral soil layers, is inverted onto undisturbed soil forming a double humus layer inside the mound and a mineral soil layer on top of the mound. The buried humus layers will decompose and provide nutrients to the seedling over the next few years, and capillary action raises water from the ground so the seedlings are not solely dependent on rainwater (Luoranen et al. 2007). Selecting mounding over patching or disc trenching produces better results, as seedling growth is enhanced in the mounded spots (Heiskanen et al. 2013; Kankaanhuhta 2014). Soil preparation in general also has a negative impact in terms of enhancing the growth of unwanted tree species that disturb the development of coniferous crop trees (Saksa et al. 1990). Spot mounding exposes only as much mineral soil as is needed, as opposed to continuous scarification by disc trenching. Spot mounding has thus been reported to reduce the need for young stand management (Uotila et al. 2010). Although spot mounding is more expensive than disc trenching, the total costs of the regeneration chain were higher in disc trenching than in spot mounding, and income from the first commercial thinning were higher on spot mounded areas based on growth simulations and investment calculations (Uotila et al. 2010).

The time consumption of spot mounding carried out with excavator boom-mounted devices with intermittent working method depends on working conditions and mound quality criteria (Brunberg and Fries 1985; von Hofsten and Pettersson 1991; Hall 1995; Rantala et al. 2010). Continuously advancing spot mounders have tended to be faster than intermittently working ones (Hämäläinen and Kaila 1985; Hall 1995; Rantala et al. 2010), but they suffer from a low number of acceptable mounds per ha in relation to the need for suitable planting spots (von Hofsten 1991; Hall 1995; Rantala et al. 2010). Also, devices with two mounding units instead of one have been reported to work faster (Brunberg and Fries 1985). Mounding can also be integrated with stump lifting to minimize costs by merging two work tasks (Saarinen 2006; Laitila et al. 2008), although work quality has been reported to be unsatisfactory (Rantala et al. 2010).

Bare-root seedlings were the only seedlings available for planting before the late 1960s. However, to improve the cost-competitiveness of regeneration and to reduce several biological and technical problems with bare-root seedling production, containerized seedlings have become the main seedling type (Nilsson et al. 2010). In 1990, 35% of domestic spruce seedlings delivered for planting were bare-root seedlings, while in 2013 the same number was only 0.1%. With Scots pine (*Pinus sylvestris* L.), the share of domestic bare-root seedlings delivered for planting in 1990 was 29% and after 2007 the share has diminished to virtually zero (Juntunen and Herrala-Ylinen 2014). Containerized seedlings are planted manually after soil preparation using a planting tube, and the quality of planting work is strongly related to soil preparation (Kankaanhuhta 2014; Juntunen and Herrala-Ylinen 2014). The time consumption of manual planting is greatly affected by working conditions and the size of the containerized seedling root plug (Räsänen 1982; Harstela 2004; Strandström et al. 2009). Stump and slash harvesting enhances productivity by creating more homogenous working conditions (Saksa et al. 2002; Saarinen 2006). Different tree species also have various recommended planting densities and the distance from the seedling storage affect the worktime required for manual planting (Harstela 2004; Äijälä et al. 2014). There are few aspects, if any, that can be further optimized to significantly improve the productivity of manual planting with planting tubes (Harstela 2004).

In Finland, forest owners are legally obliged to reforest stands after the termination of regeneration felling or intermediate felling if the remaining stand is not sufficient for creating a new stand. Regeneration must to be accomplished 10–25 years after the termination of wood harvesting and according to the Forest Act 1093/1996: “a seedling stand is considered to have been produced when it is sufficiently dense, the seedlings are evenly distributed, their average height is 0.5 metres, and their development is not immediately threatened by other vegetation”. Forest owners can influence the regeneration result within the framework of the forest act (Forest Act 1093/1996). Soil preparation is the most important factor affecting the outcome of Norway spruce plantings. Positive effects of soil preparation compared to no preparation are reported to be evident at least 18 years after planting. The first five years after planting are the most critical for seedling survival (Johansson et al. 2013). Spot mounding has been reported to provide the best results when establishing Norway spruce (Uotila et al. 2010; Kankaanhuhta 2014). Planting date also affects seedling outplanting performance. Norway spruce can be planted from May until the end of September with seedlings suitable for a given planting period (Luoranen et al. 2006). In case of Scots pine, planting is possible during two periods: from May until early June and from early August until late September (Luoranen and Rikala 2013).

Appropriate planting density is also crucial to ensure high quality timber in the future along with reasonable economic returns (Luoranen and Kiljunen 2006). Tapio Forestry Development Centre has recommended a planting density of 1800 pl ha^{-1} for Norway spruce, varying by ±200 seedlings ha^{-1} depending on soil fertility (Äijälä et al. 2014). It is important to plant tree species on suitable site types as an improper site produces poor regeneration results (Kankaanhuhta 2014). Deep planting is common nowadays, and deep-planted seedlings, i.e. with a planting depth of 5–10 cm, have been reported to survive better than seedlings planted on mounds at normal planting depths (Sutton 1967; Luoranen and Kiljunen 2006; Luoranen and Viiri 2016). If at least one third of the shoot is above ground level after planting, the development of Norway spruce seedlings is not negatively affected (Luoranen and Viiri 2016) (Figure 1).

Figure 1. A deep-planted Norway spruce seedling in a spot mound. The root plug of the seedling is in the double humus layer, and the mineral soil layer on top of the mound is 5–10 cm thick. Photo: Erkki Oksanen/Luke.

1.2 Planting machines

The first planting machines were continuously advancing and basically designed for the afforestation of obstacle-free arable land. These machines required two operators; one driver and one that inserted the seedling into some kind of pipe or dibble (Skogssektionen 1971; Bäckström 1977; Bäckström 1978, Lawyer and Fridley 1981; Berg 1990, Hallonborg 1997; Ersson 2014). The historical development of these early machines is well described in the literature (e.g. Bäckström 1977, Berg 1990 and Ersson 2014), thus in this thesis it is concentrated on single-operator planting machines for forest terrain. These kind of planting machines have been developed in Finland and Sweden since the 1970s trying to compete economically with manual planting (Skogssektionen 1971; Bäckström 1978). This development led to machines that prepare the soil continuously by disc trenching and plant pine seedlings: Serlachius in Finland and Silva Nova in Sweden. These were highly automated planting machines with a productivity of 1367 seedlings per productive work hour (pl PWh_0^{-1}) for Silva Nova and 1050 pl PWh_0^{-1} at its most productive for Serlachius (Kaila 1984; Hallonborg et al. 1995). While some concerns were about the quality of soil preparation (Adelsköld 1983), overall work quality was satisfactory (Kaila 1984; Hallonborg et al. 1995). In spite of their progress, machine planting was too expensive compared to manual planting (Hallonborg et al. 1995) and they had operational problems on high-obstacle forest terrain (Hallonborg 1997).

Machine development continued with an intermittent work approach whereby machines carried the planting units (e.g., mounted on a base machine boom) rather than dragging them behind the machine to avoid obstacles such as stumps and stones (Malmberg 1990). In the early 1980s, mechanized tree planting research and development peaked in Nordic countries when several different concepts were under development and testing (Malmberg 1990; Ersson 2014). Intermittent work with a boom-mounted planting device resulted in the Öje planter, EcoPlanter, and Ilves planting device (von Hofsten 1991; Hallonborg et al. 1995; Rummukainen et al. 2002).

Of these three planting devices, Öje Planter, currently known as the Bracke P11.a, is still in commercial use. At its best, the Ilves planting device was faster (productivity 170–250 pl PWh_0^{-1}) than manual planting, but lacked a soil preparation feature and was ultimately uneconomical compared to manual planting (Rummukainen et al. 2002). The EcoPlanter had two soil preparation and planting units working simultaneously, and thus could plant up to 400–500 pl PW_0^{-1}. Seedlings planted with the EcoPlanter faced serious problems caused by pine weevils because mounding was based on a rotation principle that mixed the humus and mineral soil layers rather than inverted them (Mattsson 1997). Pine weevils damage more seedlings growing on unprepared humus soil than on a prepared mineral soil surface (Luoranen and Viiri 2012).

Today, tree planting with excavator-based machines is more common in Finland than in other countries. An estimated 31 machines are currently in use in Finland (Rantala et al. 2009). In Sweden, the estimated number in use is less than ten, all of which are boom-mounted Bracke devices (Ersson 2014). The Bracke, M-Planter, and Risutec planting devices are used in Finland (Figure 2). M-Planter was introduced to the market in 2008 and has two parallel planting units in contrast to the single-unit Bracke and Risutec machines. The M-Planter's two planting units are separate, enabling mounding and planting with only one unit if necessary. M-Planter has a combined capacity of 242 seedlings (or 162 seedlings in the previous model) whereas Bracke has 72 seedlings (Rantala et al. 2009; Strandström et al. 2009). Risutec has three different models with capacities of 60 (PM60), 120 (TK-120), or 200 seedlings (TK-200) (Risutec 2016a). The disadvantages of the planting devices with one planting unit include low productivity because they have small seedling cassettes and plant only one seedling at a time compared to a double-unit device (Rantala et al. 2009). The productivity of M-Planter (240–260 pl PWh_0^{-1}) is reportedly higher than that of Bracke (130–198 pl PWh_0^{-1}) (Rummukainen et al. 2002; Saarinen 2006; Rantala et al. 2009; Liepiņš et al. 2011). An increase in stoniness or in the number of stumps decreases M-Planter productivity more than the Bracke machine, whereas an increase in slash cover decreases the productivity of Bracke more than that of M-Planter (Rantala et al. 2009).

Figure 2. Planting devices in use today: Bracke P11.a (left, photo: Mikko Syri), M-Planter (middle, photo: Heidi Hallongren), and Risutec TK-200 (right, photo: Jussi Aikala)

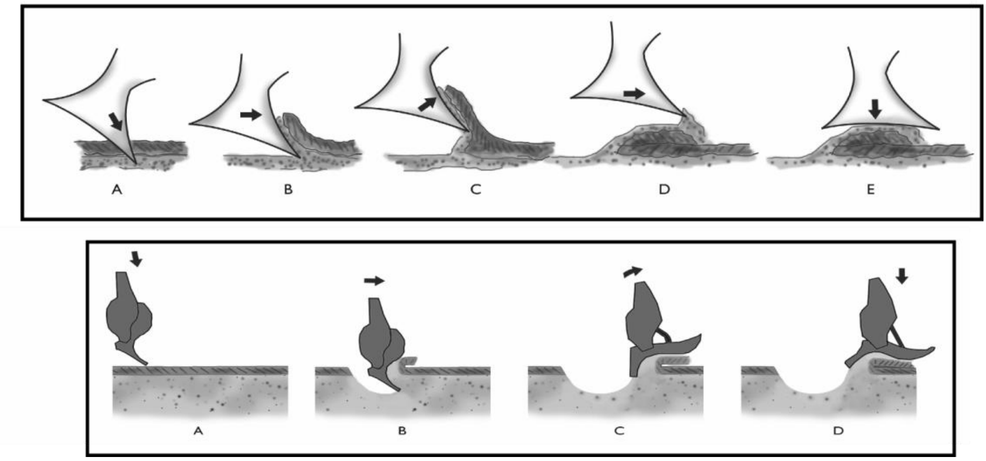

Figure 3. Soil-mounding process of the planting device with both a rigid (top) and a hydraulic mounding blade (bottom) (Laine and Syri 2012). Once a mound is formed (A–D top and A–C bottom) and compacted (E top and D bottom), the planting tube is opened, the sleeve belt in the seedling cassette transfers one seedling at a time into the tube, and the seedling is planted in the middle of the mound and soil is compacted around the seedling.

Tree-planting devices in use today consist of a mounding blade, planting tube, soil-packing shoe(s), and seedling cassette(s), and are usually mounted to the boom of the excavator. They carry out spot mounding as a soil preparation method, in which a volume of soil, including both the humus and mineral layers, is inverted onto undisturbed soil. Once the mounds are formed, seedling(s) fall automatically from cassette(s) into planting holes in the middle of each mound and soil-packing shoe(s) compact the soil around the seedling(s) (Figure 3). The operator determines the planting points individually and typically seedlings are planted along an arc from a spot selected by the operator. The machine is then moved to another spot and the process is repeated. Seedlings are stored in manually-loaded cassettes on top of each planting device and are refilled as required from a seedling storage rack, usually located at the back of the excavator.

1.3 Why plant trees mechanically?

Forest work studies, similar to work science in general, “examine work including the working human being, work conditions and technology (machines, tools, work methods, work techniques and work organization)” (Harstela 1991). The main aim of work studies is to increase productivity and optimize effort. Productivity is generally defined as the ratio of output to input, and in forest work studies it is usually presented as the ratio of work output to human labor input (Harstela 1991; Kanawaty 1992). Although cost-competitiveness and productivity are not synonymous, the same tools can be used to investigate efficiency, as increased productivity usually decreases unit costs (Harstela 2004).

According to Harstela (2004), mechanization and automation can be used to improve cost-competitiveness. The mechanization of tree harvesting has significantly decreased unit costs in the last 30 years (Figure 4) (Luonnonvarakeskus 2016; Metsäteho 2016). However, planting costs have concurrently increased by 14%. Similar technological development has not occurred in planting, although development and use of containerized seedlings over bare-root seedlings has improved productivity and reduced total costs. Although labour costs have increased, such developments have enabled planting costs to remain the same (Nilsson et al. 2010; Juntunen and Herrala-Ylinen 2014). Mechanization of tree harvesting is the key reason for a decrease in harvesting costs, and as a result the share of motor-manual felling has decreased from over 80% in 1985 to nearly zero today (Figure 4).

Tree harvesting mechanization is a result of a long developmental process. Harstela (2004) listed the fundamental principles of mechanization to be:

1) Processing appears faster than in manual work
2) Two or more work tasks or elements are performed by the same machine
3) Multi-processing is possible
4) Automatization of work elements
5) Intermittent working method is replaced by continuous working
6) Reasonable price in relation to productivity and annual utilization rate
7) Good technical availability and adequate utilization of capacity
8) Reasonable quality of mechanized work

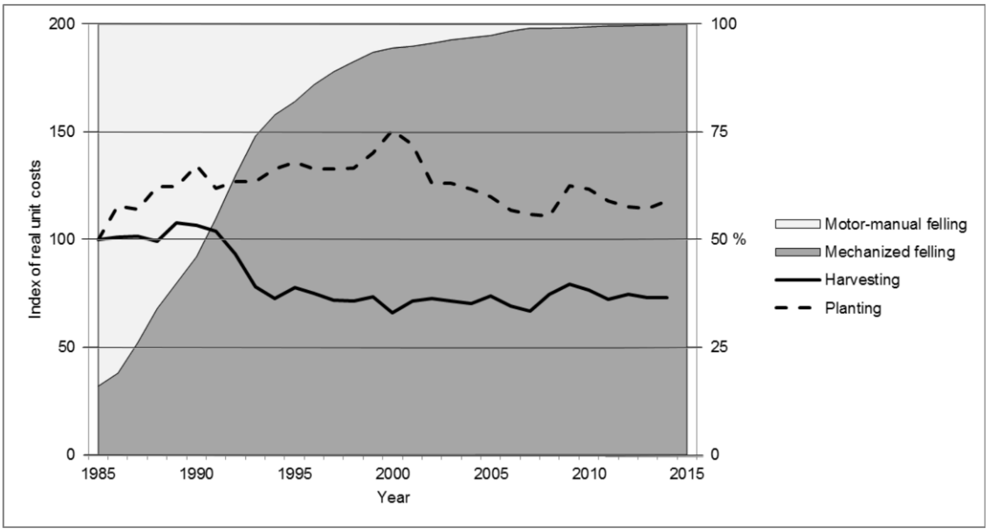

Figure 4. Index of real unit costs of planting and harvesting in non-industrial, private forests in 1985–2014 on the left y-axis and degree of mechanization in timber fellings in 1985–2015 on the right y-axis (Luonnonvarakeskus 2016; Metsäteho 2016). Relative costs of planting and harvesting in 1985 were set to 100. Monetary values are deflated using the wholesale price index (1949 = 100), including value added tax and other commodity taxes (Statistics Finland 2015). Harvesting figures include domestic logs and pulpwood harvested and transported by the largest forest industry companies and Metsähallitus, which is a state enterprise administering all state-owned forests. Harvesting also covers mechanized and motor-manual felling. The figures of mechanization in timber fellings include fellings by the largest forest industry companies and Metsähallitus.

Today, state-of-art harvesters meet the requirements set for mechanization (Harstela 2004). These steps can also be followed when mechanizing planting work. Principle two can be considered as the basis of mechanized planting, as soil preparation and planting are fitted on the same device in modern planting machines. However, the first principle is the most important, as the main goal of mechanization is higher productivity compared to manual methods. The first of Harstela's principles was studied in this dissertation and the competitiveness of mechanized tree planting compared to manual methods was addressed in Article II. In addition to this, productivity of the M-Planter planting machine was investigated in practice and in experimental conditions in articles III and IV, respectively. M-Planter is one of the first planting devices to satisfy principle three, as it has two mounding and planting units working simultaneously. Principle four was studied in Article V, which evaluated the automatization of a seedling feeding system. Principle five, replacing intermittent working method with continuous working, must be taken into account when developing new planting machines in the future. Principle five was not studied in this thesis as data were only collected from commercially-available machines currently in use. However, recommendations concerning future designs are noted in the results and discussion sections.

The machinery under development must remain simple and robust in order to maintain cost-effectiveness. Also, the more complex the machinery, the more vulnerable it is to malfunction. In practice, this might lead to higher costs and lower productivity due to longer periods of service and repair. Principle six was considered in Article I, where utilization of the planting machine capacity was investigated by interviewing planting machine contractors. Article I did not directly take a stand on planting machine prices. Investigating technical availability and work-time distribution in practice, i.e. principle seven, was the aim of Article III. Principle eight (reasonable quality of work) was taken into account in all articles (I–V). The aims of this dissertation are presented in more detail in the second chapter and in chapter 3 of the material and methods section.

Several other reasons exist for the mechanization of planting work. Firstly, the demand for labour can be evened out if seedlings can be planted mechanically from May until the end of September and base machines can conduct other work outside the planting season (Luoranen et al. 2011; Rantala and Saarinen 2006). Silviculture has a highly seasonal demand for labor, especially reforestation, as most of the planting takes place during one month in spring. Manual planting in Finnish private forests requires 650 person-years each year, which translates into a standing labor pool of approximately 4300 people (Alatalo 2011; Hallongren et al. 2012). Secondly, the supply of forest labour continues to shrink in Finland. In 2004, the share of forest workers aged 55 years and older was 23% (OSF 2016a), while in 2013 the same number was 41% (OSF 2016b). Forest owners are also aging and are thus less able to carry out the planting work themselves. Thus, industrial-scale service providers are needed to effectively provide the planting service with a minimal workforce (Alatalo 2011; Hänninen et al. 2011). Thirdly, efficient reforestation maintains and improves the profitability of investments made in forestry, and motivates forest owners to practice forestry (Uotila 2005; Harstela 2004). The increased recovery of slash (also known as logging residues) and stumps as bioenergy will improve and further increase the amount of forestland suitable for mechanized planting (Saarinen 2006). Furthermore, seedlings planted with machines perform as well or better than those planted manually (Ersson and Petersson 2011; Luoranen et al. 2011; Ersson and Petersson 2013), so it is unlikely that work quality represents a limiting factor in the application of planting machines.

The mechanized planting chain differs from the traditional manual regeneration chain. It involves several constituents with various responsibilities. The planting machine business, or contractor, is responsible for the operational work of planting the seedlings and managing work quality. From the viewpoint of the planting machine contractor, a typical client is a large silviculture and forest industry enterprise (SFIE), a local forest owners association (FOA), or a non-industrial private forest owner (NIPF). A client can be regarded as a service provider with the responsibility of planning the mechanized planting activities, ordering seedlings from the nursery, and selecting worksites suitable for mechanized planting. NIPFs usually buy a planting service from SFIE or FOA rather than employing the planting machine contractor themselves. The nurseries grow, prepare, and deliver seedlings suitable for mechanized planting to depots or worksites.

2 OBJECTIVES

The theme of this research is relevant as the demand for mechanized tree planting is expected to increase in the future. To date, mechanized planting activity in Finland and its cost-competitiveness compared to manual planting has not been the subject of a rigorous investigation. This dissertation surveyed the Finnish mechanized planting industry and its success factors (I). After observing the productivity level of mechanized planting in practice (III) and in experimental (IV) conditions, the productivity level of mechanized planting in comparison to manual planting was explored (II). A technical development, in this case an automatic seedling feeding system, was studied to determine whether the current productivity level of mechanized planting could be increased (V). The quality of planting work was also evaluated throughout the project (I–V).

The overall objective of this dissertation was to study the mechanization of tree planting in Finland and how to improve its current productivity. Objectives were studied in five research papers (I–V). The existing planting machines in operation in Finland were employed to provide the empirical data for the analysis of the specific research questions (SQs). The SQs were formulated according to Harstela’s (2004) principles of techno-economically reasonable mechanization. The SQs were:

- SQ_1: Is the productivity of mechanized planting higher than in manual work and is the work cost-competitive compared to manual methods? (Principle 1)

- SQ_2: Does automation of seedling feeding increase the productivity of mechanized planting? (Principle 4)

- SQ_3: What is the technical availability and utilization of the planting machine capacity? (Principle 7)

- SQ_4: Is the quality of mechanized planting reasonable? (Principle 8)

3 MATERIAL AND METHODS

3.1 Efficiency of mechanized planting

Work study is one of the most important methods of work science (Nordisk avtale om… 1978). The ILO Handbook (Kanawaty 1992) defines work study as “the systematic examination of the methods of carrying on activities so as to improve the effective use of resources and to set up standards of performance for the activities being carried out”. Work study can be divided into method study and work measurement, both of which aim for higher work productivity (Harstela 1991; Kanawaty 1992). Work measurement, and its principal technique time study in particular, was used to explore the productivity of planting machines (III, IV, V) after which this was compared to the productivity of manual planting (II).

The basic time concept used in forestry work studies divides the total time (TT) into workplace time (WP) and non-workplace time (NW), which includes travel time and unutilized time. WP is further divided into worktime (WT) and non-worktime (NT), which includes disturbance time (DT) and work-related delay time (WD). WT is further divided into productive worktime (PW) and supportive worktime (SW), which includes preparatory time (PT) and service time (ST). PW can be presented as PWh_{15}, which is one productive work hour including short 15 minute-or-under interruptions, or as an effective work hour PWh_0 excluding all interruptions. These time concepts can be used to determine mechanical availability (MA), machine utilization (MU), total utilization (TU), degree of operation (OP), and degree of repair for the machine units (REP) (Nordisk avtale om… 1978; Björheden and Thompson 2000). This dissertation concentrates mostly on productive worktime, but non-worktime and supportive worktime are also discussed as part of the mechanized planting work.

3.1.1 Productivity

The productivity of the M-Planter planting device was studied in practice (III) and in experimental conditions (IV) (SQ_1) to find out the productivity of a multi-processing double-unit planting device. Besides exploring the productivity of the M-Planter, the productivities of Bracke and Risutec APC planting devices were also studied (V).

In Article III the operation of five machine units managed by 13 operators was followed throughout the 2008 and 2009 planting seasons. Three worked during the 2008 season and three during the 2009 season, one machine being used during both seasons. None of the operators had worked with the M-Planter before, but most had experience in working with either an excavator or a harvester. Operation of the machine units was followed with filling out paper forms in which the operators marked their work-shift-specific working hours, the number of seedlings planted, and interruptions in chronological order. All in all, the follow-up data consisted of 643 observations (from 607 work shifts). The number of work shifts per operator varied between 10 and 89. During the follow-up, 325 hectares were planted on 95 regeneration sites.

In Article IV, six operators worked with four machines during the 2010 planting season. Operators had two or more planting seasons of experience with the planting machine. The data were obtained from 1–3 observations per operator in each of two planting areas, yielding a total of 20.64 hours during which 7010 seedlings were planted. All work study data were videotaped. The observation was the time taken to plant seedlings from two planting cassettes. The average number of seedlings planted during one observation was 234 (SD 20.9). If the two cassettes did not empty at the same time, the work was stopped when the first cassette became empty. Machine breakdowns also affected the number of seedlings planted per observation. The time used to refill the cassettes was not measured, as it was assumed to be constant among operators.

In Article V, the data were collected in two clear-cut areas where stumps and slash debris had been removed. The two research areas were divided into two, and both machines were used by both operators at all four sites. The order and combination of operator and machine was randomly chosen for each site. All work study data were videotaped. An observation unit for the Risutec APC was two cultivation trays (162 seedlings), with the exception of operator 2 on planting area 4 (153 seedlings). An observation unit for the Bracke was two seedling cassettes (178 seedlings), with the exception of operator 1 on planting area 3 (162 seedlings). The time spent reloading the seedling cassettes was included in the productive worktime of the Bracke. The time used loading the seedling storage racks was also videotaped and both operators loaded both machines twice. The data comprise a total of 14.3 hours taken to plant 2695 seedlings.

In Articles IV and V, a stopwatch time study based on continuous timing was employed, where a clock runs continuously and the time elements are separated from each other by codes (Harstela 1991). Productivities were obtained from video data and were presented as PWh_0. In Article III, work-shift-specific productivity figures were calculated for the operators on the basis of the paper forms. The TT of the devices was divided into WP, relocation time, and time used for maintenance and repair activities. WP was still divided into PW_{15} and further into PW_0. These time concepts were used to determine MA, MU, TU, OP, and REP for the machine units.

For statistical analyses, linear mixed models were used with restricted maximum likelihood (REML) estimation (III, IV, and V). A linear mixed model incorporates parameters for both fixed and random effects (McCulloch and Searle 2001). Random effects are considered as a random sample of the population of interest. Linear mixed models were used to examine the effects of different variables on productivity (III, V) or time consumption (IV) of the planting work. The variable selection method was backward elimination, in which all variables were entered into the equation and then sequentially removed until the final set contained only those found to be statistically significant at the 0.05 level. For instance, a linear mixed model can be represented as follows (Eq. 1):

$$y_{ijk} = \alpha_0 + \mathbf{x}_{ijk}'\boldsymbol{\alpha} + a_i + b_j + e_{ijk} \qquad (1)$$

where,

α_0 = intercept
$\mathbf{x}_{ijk}$ = vector of explanatory variables
$\boldsymbol{\alpha}$ = vector of fixed-effect coefficients
a_i = random effect *i*, (*i* = 1,…,n)
b_j = random effect *j*, (*j* = 1,…,n)
e_{ijk} = residual error

Table 1. Variables used in the linear mixed models in Articles II, IV, and V divided into fixed (F) and random (R) effects.

Variable	Article III	Article IV	Article V
Work difficulty factors	F	F	F
Operator	R	R	F
Worksite	-	R	R
Operator's prior experience of machine work	F	-	-
Cumulative experience of working with M-Planter	F	-	-
Base machine	-	F	-
Planting device	-	-	F

Work difficulty factors, operator, and operator's prior experience of machine work and cumulative experience on working with the M-Planter were used in the model in Article III (Table 1). The variables used in Article IV were work difficulty factors, planting area, base machine, and operator, and in Article V they were planting device, operator, work difficulty factors, and work site. In Article III, the effect of the work difficulty factors were considered fixed, as were the operators' experiences in terms of earlier machine work experience and the number of seedlings planted with the M-Planter before each work shift, while the rest of the effects caused by the operators were considered random. In Article IV, work difficulty factors and the base machine were considered fixed factors, and the effects caused by the operator and worksite were considered random effects. In Article V, work difficulty factors, planting device, and operator were treated as fixed effects, whereas worksite was treated as a random factor. Based on linear mixed models, productivity was visualized as a function of statistically significant work difficulty factors on average working conditions (means weighted with size of the planting area).

3.1.2 Competitiveness

To address SQ_1, the costs and time consumption of mechanized planting, either with single- (i.e. Bracke P11.a, referred to as PLANT1) or double-planting units (i.e. M-Planter, referred to as PLANT2) and manual planting were evaluated. Prior to manual planting (MP), the spot mounds were created with either a mounding blade mounted to the boom of a medium-sized (15-ton) excavator (SPOT) or with a continuously advancing spot mounder fitted onto the rear of a medium-sized (14-ton) forwarder (CONT). Planting devices were fitted onto medium-sized (15-ton) excavators. Configuration of the planting activities along with time consumption and productivity are summed up in Table 2.

Results were presented in relative units, where a value of 100 corresponds to the spot mounding followed by MP. Cost calculations were based on activity-based costing (ABC), which exposes the relationships between activities and resource consumption (Cooper & Kaplan 1991, Edwards 2008). All fixed and variable costs originated from the purchase and use of silvicultural devices. Fixed costs of the base machine were divided into silvicultural work and other activities in relation to the annual number of productive hours. Costing was based on the purchase and use of new devices and new base machines.

Table 2. Configuration, time consumption (hE_{15} ha^{-1}), and productivity (unit PWh_{15}^{-1}) of planting machines used for each activity in Article II.

Type of work	Manufacturer and model of silvicultural device	Base machine	Time consumption (hE_{15} ha^{-1})	Productivity (unit PWh_{15}^{-1})	Reference
Spot mounding					
SPOT	Naarva	Excavator (15 t)	6.00	0.17[a]	Saksa et al. 2002, Saarinen 2006
CONT	Bracke M.26	Forwarder (14 t)	1.11	0.90[a]	Saarinen 2006
Mechanical planting					
PLANT1	Bracke P.11a	Excavator (15 t)	12.00	150[b]	Arnkil 1997
PLANT2	M-Planter	Excavator (15 t)	11.92	151[b]	Article III
Manual planting					
With SPOT			10.93	165[b]	Metsäalan työehtosopimus (2010)
With CONT			11.39	158[b]	Metsäalan työehtosopimus (2010)

[a] = ha PWh_{15}^{-1}
[b] = pl PWh_{15}^{-1}

A tool for analyzing the profitability of various soil preparation and planting methods was developed using Microsoft Excel. For calculating the costs of various methods, a system analysis model of soil preparation and planting costs was developed. Figures used in the cost calculations were based on 2011 information and are presented in Table 3.

Table 3. The main parameters used in the cost calculations of Article II.

	Spot mounding		Planting	
	SPOT	CONT	PLANT1	PLANT2
Annual total use, base machine (h)	2196	1838	2126	2126
Silvicultural use (h)	1448	1090	1242	1242
Silvicultural use (ha)	241	982	104	104
Fixed costs				
Purchase price, base machine (€)	125 000	200 000	125 000	125 000
Purchase price, add-on device (€)	4500	100 000	44 000	49 000
Annual administration, insurance, etc. (€)	7600	8550	7600	7600
Variable costs				
Fuel costs (€ h^{-1})	8.5	14.9	8.5	8.5
Relocation costs, machine (€ km^{-1})	10.0	4.5	10.0	10.0
Maintenance and repair (€ h^{-1})	5.0	8.0	5.0	5.0

3.1.3 Quality

Field inventories were carried out to estimate the quality of planting work (SQ_4) along with work difficulty factors. Inventories were performed either by a systematic regular-shaped grid of the circular sample plots (r = 2.52 m) on regeneration areas (III) or on three plots (r = 3.99 m) located systematically in the middle of the excavator tracks after planting was complete (IV, V). Planting quality was evaluated in terms of planting defects and seedling density, but mound quality was also evaluated. Planting defects included insufficient compaction of the soil around the seedling, inappropriate planting depth, soil or slash on top of the seedling, physical damage, incorrect seedling orientation, and the number of empty and multiple plantings. A planting service provider had set the target density of planting work at 1800 seedlings per hectare. All planted seedlings were Norway spruce. Work difficulty factors were measured in terms of slash, ground inclination, number of surface obstacles and the stumps, stoniness, and thickness of the humus layer in all three studies (III–V).

3.2 Utilization of planting machine capacity

All registered businesses that provided a mechanized tree planting service in Finland during 2013 were interviewed in person in March and April 2014 to study the utilization of the planting machine capacity (SQ_3) (I). At the beginning of 2014, a total of 28 businesses were identified as operating a mechanized tree planting service, 22 of which were active during 2013. Two businesses did not participate in a full interview, but a non-response analysis covering the key questions concerning machinery and equipment in use, along with the amount of mechanized planting work that was completed in 2013, was included. Their data were merged with those obtained from the full interviews and some analyses were conducted on this (20+2) data set.

Interview questions were mainly structural, aiming to understand the utilization of the planting capacity, worksite characteristics, seedling quality, and logistics. For determining critical success factors (CSFs), respondents were asked to evaluate 12 factors in terms of their importance and impact on the productivity and cost-effectiveness of mechanized planting in general. Next, respondents evaluated how these 12 factors were realized in 2013 based on their perceptions. Evaluations were made on a five-level Likert scale. Open questions concerning the development and efficiency of mechanized planting in the future were also asked.

For statistical analyses, mean values (arithmetic means) and standard deviations (SD) were calculated. Site-specific variables were calculated as means weighted with the total area planted by the contractor. Due to a small data set and relatively slight differences in the population, a deeper statistical analysis was not carried out. Gap analysis methodology was used to compare the 2013 performance of CSFs with their perceived importance. This involved the comparison of actual performance (realization) with the importance of the factor in question. This allows one to see which aspects need improving and which must be taken into account. Paying attention to unimportant aspects is irrelevant despite the realization of that factor being poor. The gap was calculated as follows (Eq. 2):

$$G_i = R_i - I_i \qquad (2)$$

where,

G_i = gap of the success factor *i*
R_i = realization of the success factor *i* in 2013
I_i = importance of the success factor *i*.

3.3 Development of planting machines

A comparative time study approach was used to determine whether the automation of seedling feeding increases productivity compared to the manual refilling of seedlings (SQ_2). The difference between the currently used Bracke planting device, with manual seedling refilling, and the new prototype Risutec APC, with an automatic seedling feeding system, was evaluated (V). In July 2013, two operators worked with both machines. Both operators had several years of experience with mechanized planting, although one was more familiar with Risutec APC and the other with the Bracke. The operators were given one work day to familiarize themselves with machines.

Although the Brackes in use today typically contain a maximum of 72 seedlings, the device used in the study was one of the first ones with an original capacity of 90 seedlings. The seedling storage rack attached to the base machine had a capacity of 2080 seedlings: 13 plastic trays each containing 160 seedlings. Cultivation trays were reusable with dimensions of (L×W×H) 4000×6000×1000 mm. Seedlings were manually transferred from cultivation trays to plastic trays at the nursery. The Bracke was mounted on the 7.1-m boom of a 14-ton Hyundai R140LC-9 excavator.

Risutec APC was designed and built by Risutec Ltd. and UPM Forest, and is based on the Risutec TK200 planting device (Figure 5). The Risutec APC was a prototype that had briefly been tested in forest terrain. It was mounted to the 7.7-m boom of an 18-ton Hyundai R180LC-7 excavator. The planting device weighs approximately 1800 kg and its dimensions are (L×W×H) 2311×2435×2359 mm (plant container alone 1380×2435×1394 mm).

Seedlings were reloaded in trays, relieving the operator of the need to manually reload the seedlings one at the time. Each cultivation tray (BCC Plantek 81) contains 81 (9×9) seedlings and measures (L×W×H) 385×385×73 mm. While loading the seedling storage rack, seedlings in each cell must be manually deplugged from the rigid cultivation trays using push rods to loosen the root plugs. The planting device holds up to 16 cultivation trays on two levels corresponding to a total of 1296 seedlings (Figure 5). After planting the seedlings from the lowermost level, the upper layer descends for the work to continue. The Risutec APC also has a separate seedling storage rack containing 12 trays (972 seedlings) located at the planting site, for additional seedling requirements. The loader, located in the middle of the Risutec APC device, selects one row of nine seedlings from the cultivation tray at a time, alternating between the left and right sides. After selection, the nine seedlings are loaded into the feeder while the entire machine remains stationary. Seedlings are planted one at a time, and once the seventh seedling is planted, the loader begins to select another nine seedlings from the cultivation tray. After the ninth seedling is planted, the feeder returns to resupply while the mounds can be formed. The planting cycle is repeated until all the cultivation trays are emptied or the work is complete.

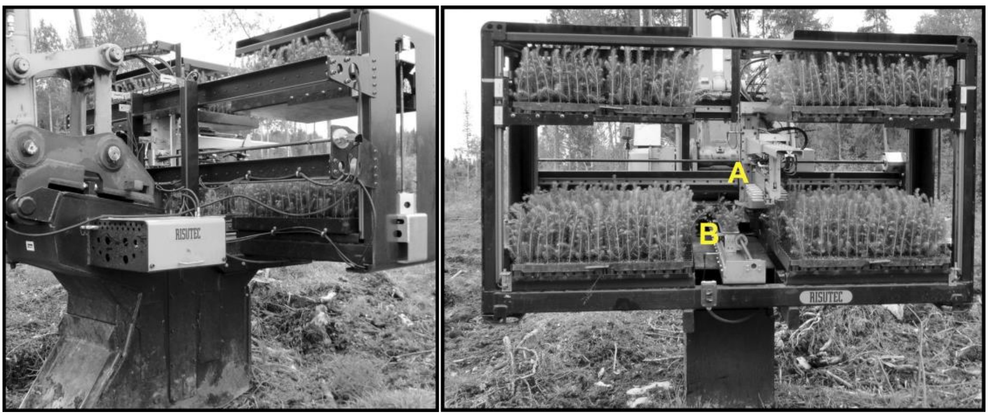

Figure 5. Risutec APC planting device. Loader (A) selects one row of nine seedlings from the cultivation trays and loads them into the feeder (B), from which they are planted one at the time. Photos: Tiina Laine.

Results included the total and unit costs of Bracke and Risutec APC derived from time study and cost calculation analyses. In addition, total and unit costs for an idealized planting device with an automatic feeding system (AUT) were estimated by applying the same results derived from the time study. AUT was assumed to be similar to the Bracke planting machine with the only difference being the automatic feeding. Thus, figures for AUT are based on Bracke plus an added investment cost, with the exception of the figures concerning the automatic feeding system based on the Risutec APC (i.e. capacity, time needed to load the plant container and seedling storage rack, need for maintenance and repair, etc.). The analysis identified the circumstances under which an AUT would be cost-effective.

Cost calculations were based on activity-based costing (ABC), which expresses the relationship between activity and resource consumption (Cooper and Kaplan 1991; Edwards 2008). Productivity values used in the cost calculations were derived from the time study (a ratio of 1.10 from PWh_0 to PWh_{15}). A tool for analyzing the profitability of various planting devices was developed using Microsoft Excel. Figures used in the cost calculations were based on 2013 information and are presented in Table 4.

Table 4. The main parameters used in the cost calculations of Article V.

	Risutec APC	Bracke	AUT
Annual total use, base machine (h)	2580	2580	2580
Silvicultural use (h)	1290	1290	1290
Fixed costs			
Purchase price, base machine (€)	125 000	125 000	125 000
Purchase price, add-on device (€)	80 000	45 000	77 000
Annual administration, insurance, etc. (€)	7700	7700	7700
Variable costs			
Fuel costs (€ h^{-1})	9.50	9.50	9.50
Relocation costs, machine (€ km^{-1})	10.0	10.0	10.0
Maintenance and repair (€ h^{-1})	6.0	5.0	6.0

4 RESULTS AND DISCUSSION

4.1 Efficiency of mechanized planting

4.1.1 Productivity

Productivity is affected by the machine, environment, and operator. Productivities reported for a double-unit planting device have been higher than for single-unit devices. Productivity of the M-Planter planting machine was 158 pl PWh_0^{-1} in practice (III) and 280 pl PWh_0^{-1} (IV) in experimental conditions (Table 5). Productivity of Bracke was 244 pl PWh_0^{-1}, while the productivity of Risutec was 20% lower compared to Bracke (196 pl PWh_0^{-1}) (V). Liepiņš et al. (2011) measured a productivity of 260 pl PWh_0^{-1} for the M-Planter in Latvia. Rantala et al. (2009) reported the productivity of M-Planter to be 236 pl PWh_{15}^{-1}, which was 36% greater than that of Bracke (174 pl PWh_{15}^{-1}).

The operator and his skill level was singled out as the most important factor affecting productivity and cost-efficiency of mechanized planting from 12 listed critical success factors (importance: 4.90) (I). Earlier experience of working with either an excavator or a harvester explains a large proportion of the variety in productivity among operators ($p<0.001$); the mean productivity of an experienced operator was 65% higher than that of a beginner in average working conditions. All operators used the M-Planter planting device for the first time and learned, on average, to use the combination of the M-Planter and a base machine more effectively during the follow-up as their experience in planting work increased ($p<0.001$). Mean productivity was 15% lower during the first planting season (143 pl PWh_0^{-1}) compared to the second season (169 pl PWh_0^{-1}). However, a closer look at the planting experience and operator variables indicates that a large portion of the variation exists in learning efficiency between operators. The planting units used by the least experienced operators additionally spent more time in repair and in other activities outside efficient planting work (III). Also, the operator more familiar with the Bracke had 46% higher productivity (290 pl PWh_0^{-1}) using it than the operator with no prior experience with the Bracke machine (199 pl PWh_0^{-1}) ($p=0.00$) (V).

Table 5. Mean productivities (pl PWh_0^{-1}) of planting machines in Articles III, IV, and V.

Article	Planting machine	N	Productivity, pl PWh_0^{-1}	Min.	Max.	SD
III	M-Planter	6	158	0	360	41.0
IV	M-Planter	6	280[a)]	235	414	32.8
V	Risutec APC	8	196	169	235	23.4
V	Bracke	8	244	177	317	55.5

[a)] Productivities included added constant seedling refilling time of 2.26 seconds pl^{-1} according to Rantala et al. (2009)

Of all environmental variables, work difficulty factors probably affect the productivity of mechanized planting work the most. Increased stoniness (III, V) (Figure 6), higher stump density (III), and higher surface obstacle density (IV) (Figure 7) were work difficulty factors that significantly ($p<0.05$) lowered productivity. Also, a thicker humus layer reduced productivity ($p<0.06$), but was not below the significance level of 0.05 (III). Stoniness (V) affected productivity the most: if stoniness increased from 20% to 60% productivity decreased 44 pl PWh_0^{-1} (Figure 6). Surface obstacles, such as stones and stumps, make it difficult to locate appropriate places to form spot mounds. Collection of slash and stumps for energy increased productivity of mechanical planting work (Saarinen 2006; Rantala et al. 2009). Slash and stumps were harvested from 62% and 33% of worksites on 2013, respectively. Stoniness was low at 28% of the worksites and high at 21% of the worksites (I).

From the 12 listed CSFs, planting machine contractors rated the harvesting of slash (importance: 4.35) to be more important than low levels of stoniness (importance: 4.30) or stump harvesting (importance: 3.00). Realization of CSFs was poorest at worksites that were stony (realization: 3.15) and where no slash (realization: 3.50) or stumps (realization: 3.11) had been removed. The greatest gap between the realization and importance of CSF, i.e. the factors that planting machine contractors consider important but which had poor performance in 2013, was observed for working conditions at sites that were stony (gap: -1.15) or where slash removal was poor (gap: -0.85). (I).

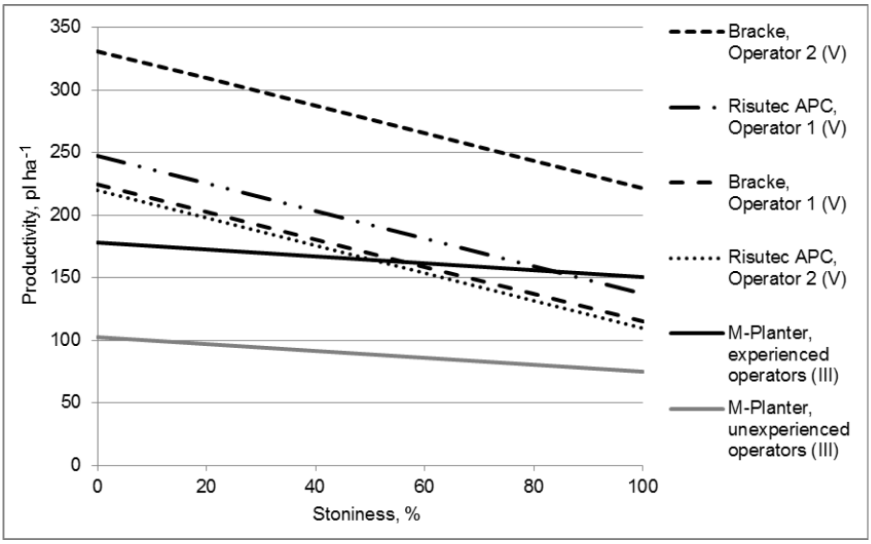

Figure 6. Effect of stoniness on productivity based on linear mixed models on Articles III and V. Stoniness is presented as percentage proportion of points with stone. Other work difficulty factors were taken into account as means weighted with size of the planting area.

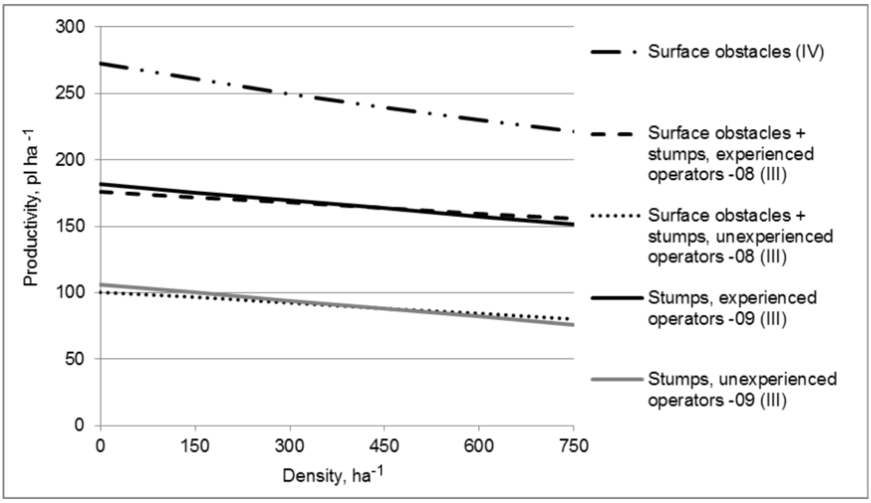

Figure 7. Effect of surface obstacles and stumps on productivity of M-Planter based on linear mixed models on Articles III and IV. Surface obstacles and stumps are presented as hectare density (ha^{-1}). In Article IV, mean time consumption ($s\ pl^{-1}$) was used in linear mixed-effect model and converted to productivity ($pl\ PWh_0^{-1}$) for visualization including a constant refilling time of 2.26 $s\ pl^{-1}$ according to Rantala et al. 2009. In Article III, stumps were included in surface obstacles in 2008, but in 2009 they were considered separately from other surface obstacles. Other work difficulty factors were taken into account as means weighted with size of the planting area.

4.1.2 Competitiveness

At a productivity level of 150 pl PWh_{15}^{-1}, the costs of mechanized planting are 23% more than for spot mounding and manual planting (Figure 8). To compete with manual planting, the productivity of mechanized planting should be at least 190 pl PWh_{15}^{-1}. (II). Figures used in the calculations were based on follow-up studies (Article III, Arnkil 1997) and productivities reported in the time studies have been higher than in follow-up studies, especially for double-unit planting devices. A skilled operator could reach the productivity required to make mechanized planting work cost-effective compared to manual planting, as great variation occurs in operator productivity, as previously shown in chapter 4.1.1.

The current advantage of planting machines is that they enable a more efficient use of labour because of lower time consumption than manual techniques. Mechanized planting requires 20% less time to perform the same work as spot mounding and manual planting (Figure 8). (II). This advantage will become more important as the supply of forest workers is shrinking (Alatalo et al. 2011). Mechanical planting can also be considered efficient when examining the entire chain from nursery to final harvest. Although the work itself might be more expensive than manual planting, mechanical planting purportedly requires less supervision when two work tasks (mounding and planting) are performed simultaneously. Cost savings could also be made with respect to seedling management and transport.

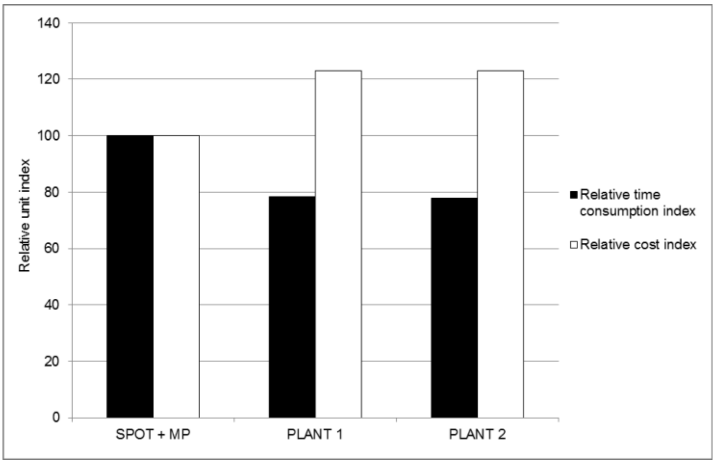

Figure 8. Relative unit costs and time consumption of mechanized planting with a single- (PLANT 1) and double-unit planting device (PLANT 2), and a combination on spot mounding followed by manual planting (SPOT + MP). Relative costs and time consumption of SPOT + MP were set at 100 (II).

The competitiveness of mechanized planting compared to manual planting can be improved by increasing the worksite area, as the increment in worksite area decreases the relative time consumption. Machine relocations also affect competitiveness, as machine relocation between worksites is expensive in terms of direct relocation costs and worktime consumption. Planting machines had a lower proportion of time spent relocating due to more time being spent preparing the soil and planting than spot mounding and manual planting. Relocation costs depended on the number and area of worksites, the distances between them, and productivity of the machine unit. The effect of the average worksite area was significant. The proportion of worktime spent relocating the machine was doubled when the average worksite area fell from 5.5 ha to 2.5 ha (Figure 9). (II).

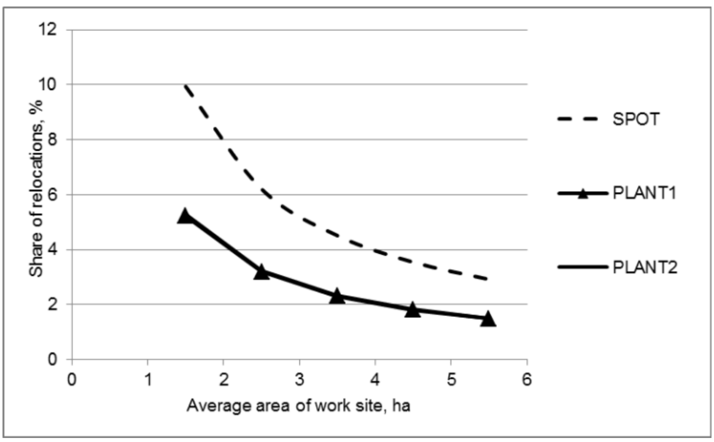

Figure 9. Effects of the average worksite area (ha) on the proportion (%) of work time needed for relocation of a single- (PLANT 1) and double-unit planting device (PLANT 2), and a spot mounder (SPOT) (II).

Principle one (i.e., mechanized processes are faster than manual work) of Harstela's (2004) list is met in that the productivity of mechanized planting is higher than that of manual methods. However, the costs of mechanized planting are not yet competitive in comparison to manual work. Productivity of mechanized planting, as well as other machine work, is affected by the machine, environment, and operator. Increasing efficiency of mechanized planting work remains possible by skilled operators and proper worksite selection as seen in chapter 4.1.1. Also, improvements to machines could increase their productivity (see more in chapter 4.3) and thus make the more competitive.

4.1.3 Quality

The follow-up study on the M-Planter (III) showed the average proportion of seedlings expressing some planting defect to be 31%, while the same numbers were 20%, 15%, and 25% in the work studies for M-Planter (IV), Bracke (V), and Risutec (V), respectively (Table 6). The most common planting defects were inadequate soil compaction, and too shallow planting depth, which together constituted more than 70% of all planting defects. Only 3–5% of defects were estimated as fatal. No significant correlation was observed between productivity and the share of planting defects for M-Planter ($p = 0.6$) (IV) Bracke ($p = 0.94$) (V), or Risutec ($p = 0.29$) (V).

Planting density was somewhat lower in the follow-up study (M-Planter 1865 pl ha^{-1} [SD 216.0] [III]) than in the work studies (M-Planter 1900 pl ha^{-1} [SD 180.0] [IV], Bracke 1850 pl ha^{-1} [SD 297.6] [V], and Risutec 2000 pl ha^{-1} [SD 282.8] [V]) (Table 6). However, it is worth keeping in mind that planting density has some effect on both time consumption and the relative unit cost of planting. Higher planting densities had lower relative unit costs but consumed more time. Time consumption increased 13–20% when planting density increased by 300 pl ha^{-1} (II). Nearly all seedlings were planted in mounds, and nearly all mounds were placed so that stones, slash, or water did not adversely affect the growing conditions of the seedling (III, IV, and V).

Table 6. Planting density (pl ha^{-1}) and the percentage of seedlings expressing some planting defect (%) (III, IV, V).

Article	Planting machine	Planting density, pl ha^{-1} N	Mean	Min.	Max.	SD	Planting defects, % N	Mean	Min.	Max.	SD
III	M-Planter	95	1865	1300	2450	216.0	95	32.4	6.5	69.8	13.4
IV	M-Planter	30	1900	1600	2400	180.0	30	19.6	0.0	50.0	13.8
V	Risutec	8	2000	1600	2400	282.8	8	25.0	10.0	40.0	11.3
V	Bracke	8	1850	1600	2400	297.6	8	15.4	0.0	36.4	12.0

Although most seedlings were planted correctly in high-quality mounds, a significant number of seedlings expressed minor planting defects. However, only a very small proportion of the defects were as assessed as being fatal. It is not usually desirable to increase planting productivity at the expense of quality, because poor work at this early stage can have negative effects throughout the lifespan. Planting machine contractors evaluated “high-quality planting work” to be the second most-important factor of the 12 listed CSFs that affect the productivity and cost-efficiency of mechanized planting (importance: 4.80) (I). Also, the realization of high quality planting work was highest in 2013 (realization: 4.35), so the quality of mechanized planting work can be considered good and it does not preclude its application.

The quality of mechanical planting has been reported to be at least as good as that of manual planting (Saarinen 2006; Rantala et al. 2009; Ersson and Petersson 2011; Luoranen et al. 2011; Ersson and Petersson 2013). With respect to the target seedling density of 1800 pl ha^{-1} set by Finnish forest management practice recommendations by the Tapio Forestry Development Centre (Äijälä et al. 2014), planting quality was excellent in Articles III–V. The average number of Norway spruce seedlings planted manually in southern Finland has been reported as 1388 pl ha^{-1} (SD 378) (Kankaanhuhta 2014), which is below the recommended target (Äijälä et al. 2014). Planting machines plant seedlings deeper than manual worker (Luoranen et al. 2011, Luoranen and Viiri 2016) and deeply-planted seedlings have been reported to survive and grow better than those planted at more shallow depths (Luoranen and Viiri 2016). Another advantage of machines is that they have power to plant seedlings deeper and more consistently than manual workers that can be fatigued. Compared to manual planting, the quality of mechanized planting can be considered good in terms of seedling density and planting depth. Thus, principle eight of Harstela’s (2004) list is met by mechanized planting.

4.2 Utilization of planting machine capacity

In 2013, 22 businesses operated 31 planting machines in Finland. Most businesses owned one planting machine, approximately one third owned two, and one business owned three. The most common planting device was the Bracke P11.a (18 devices), along with 11 M-Planters, and 2 Risutecs. Most of the planting devices were mounted on the booms of 14–21-ton excavators, but two devices were harvester-based. Ten years ago, less than a fifth of contractors provided a mechanized planting service but new contractors have since entered the market. Of the client groups, SFIEs were the largest (e.g. Stora Enso Wood Supply Finland, UPM Forest, Metsä Group). (I).

In Finland, the planting season mostly began at the beginning of May and was completed by mid-October. Therefore the average length of the planting season was 19.8 weeks (i.e. 138 days or 4.9 months) (Table 7). During the planting season, 41% of machines had a planting work stoppage for an average period of 1.2 weeks (0–8 weeks), and 42% of these were employed in other tasks (e.g. soil preparation, ditching, forest-road construction, and stump lifting) during these periods. Outside the planting season, base machines remained in operation (e.g. wood cutting, soil preparation, ditching, and stump lifting) for an average of 2.9 months (0–8 months). Each planting machine planted an average of 151 242 seedlings (SD 69 979) on an average area of 86 ha (SD 39.9). Assuming a 5-day workweek, the average productivity of the mechanized planting was 0.92 ha and 1614 pl work day^{-1}. (I).

Table 7. The extent of the Finnish mechanized planting operations during the 2013 planting season (I).

Parameter	Unit	N	Average	Min.	Max.	SD
Planting season	weeks	29	19.8	13.1	24.9	3.19
Stoppage	weeks	29	1.2	0	8	1.97
Other work during planting season	weeks	29	0.8	0	8	1.93
Planting season excluding stoppages	weeks	29	18.6	11.1	24.8	3.60
Other work outside the planting season	months	29	2.9	0	8	1.92
Planted area	ha	31	85.9	25.0	177.0	39.9
Planted seedlings	pcs	31	151 242	45 000	320 000	69 979.7

One third of the machines planted less than 60 ha yr^{-1}, and the overall average was less than 90 ha yr^{-1}. More than one third of machines were used for a single shift. (I). From the TT spent on working with the M-Planter, 68% and 13% were spent on primary planting work and refilling seedling cassettes, respectively. Thus, the average proportion of PW to TT was 80%. Of TT, 8% was categorized as other reasons such as short breaks (less than 15 minutes), relocation time, and interruptions caused by supervision of the planting work. Of remaining TT, maintenance and repair of M-Planter was the most time consuming (6%) before operator-based interruptions (3%) and excavator-based interruptions (3%). Mechanical availability (MA) for working with M-Planter averaged 89%. (III). MA is in line with other forest machine work, as the MA of single-grip harvesters has been reported as 85% and the MA of forwarders 88% in 2008 in Sweden (Nordfjell et al. 2010).

The increased use of mounding as a soil preparation method is reflected by todays planting machines, which use this method prior to planting. The planting area has almost doubled in 10 years: 1420 ha were planted mechanically in 2003, which accounted for 1.6% of all plantings, while in 2013 the equivalent numbers were 2663 ha and 3.5%, respectively (Table 8). The planting area target for the 2014 planting season was estimated at 96 ha (SD 34.8), and the potential could reach 120 ha (SD 50.7). The most important factors limiting the potential from being reached were a lack of suitable worksites within the operational range, worksite stoniness, lack of skilled operators, general weaknesses of worksites, poor operational planning, and worksite size and inclination. (I).

In 2003, there were 14 businesses operating with 16 planting machines: ten Bracke, two Ecoplanter, and four Lännen FP-160 planting devices (Vartiamäki 2003) (Table 8). These planting devices were attached to six harvesters, seven excavators, and three forwarders. The use of harvesters and forwarders has dwindled as excavators have become the preferred base machine. The main reason for this shift is that all planting machines in use today also carry out mounding (i.e. the Ecoplanter and Lännen planting devices did not mound), and an excavator boom is more suitable for digging than other forest machines (cf. Kärhä and Peltola 2004). The average number of planting machines owned by a business has risen slightly in ten years.

Table 8. Comparison of the Finnish mechanized tree planting industry in 2003 (Vartiamäki 2003) and 2013 (Article I).

Parameter	Unit	2003	2013	Difference to 2003, %
Number of planting devices	pcs	16	31	93.8
Number of businesses	pcs	14	22	57.1
Planting machines per business	pcs	1.14	1.41	23.7
Number of planting devices	pcs	16	31	93.8
Bracke		10	18	80.0
Lännen		4	0	-
Ecoplanter		2	0	-
M-Planter		0	11	-
Risutec		0	2	-
Amount of work	ha	1420	2663	87.5
Planted seedlings	million pcs	2.5	4.7	88.0
Relocation distance	km	25[a)]	22.2	-11.2
Working range	km	100	62	-38

[a)] 20–30 km in literature

Good technical availability and adequate utilization of capacity are also listed by Harstela (2004) (principle 7). In 2013, planting machines were under-utilized which negatively affects their appeal. To be cost-effective in Finland, the annual capacity of a planting machine should be 130–150 ha. However, increasing the annual capacity might also create some disadvantages in the form of greater relocation distances, poorer worksite conditions and difficulty finding competent operators (I). Nevertheless, a large potential exists for increasing the mechanized planting industry in Finland because nearly all sites that are currently mounded by excavators and planted manually could also be regenerated mechanically. The technological potential of mechanized planting has been estimated at circa 90%, representing approximately 180 units that are employed at the current productivity level (Strandström et al. 2009). According to Rantala and Saarinen (2006), the demand for planting machines in Finland would be approximately 225 units on the assumption that 50% of regeneration sites >0.75 ha are mechanically planted.

Data on the use of planting machines outside Finland is unavailable, but at least some trials have been carried out in the UK (Drake-Brockman 1998), Ireland (Nieuwenhuis and Egan 2002), and Latvia (Liepiņš et al. 2011). Keane (2006) estimates that there are over fifty Bracke planting machines working in Europe alone. An opportunity may exist for mechanized planting in other boreal countries such as Canada. There have also been some trials in tropical plantations. Risutec Ltd. have designed a new planting device and Bracke has modified the P11.a planting device to plant hardwoods, such as eucalyptus, especially in plantations (Bracke 2016, Risutec 2016b), but there are no available data concerning the use or performance of these machines.

4.3 Development of planting machines

Planting machine contractors suggested that developing existing devices and making them more reliable could enhance productivity and the cost-efficiency of mechanized planting (I). This is necessary to enhance contractor's profitability. Possibilities for improving the productivity of current planting devices could include an enlarged seedling cassette and automatized seedling loading (e.g. Ersson 2014). As the speed of mounding and planting increases, manual reloading of the seedling cassette becomes a limiting factor affecting productivity, and the need for an automatic feeding system becomes acute (Figure 10). At a productivity of 100 pl PWh_0^{-1}, the proportion of PWh_0 spent handling seedlings was 7% for Bracke (MAN) and 2% for an idealized planting device fitted with an automatic seedling feeding system (AUT), whereas at 300 pl PWh_0^{-1} the corresponding figures were 19% and 6%, respectively. An effective automatic feeding system could increase the productivity of mechanized planting. (V). In Sweden, Ersson et al. (2014a) found that the MagMat, an automatic feeding system for Bracke planting devices, increased planting machine productivity by 9% and an automatic seedling feeding system for a double-unit planting device (i.e. M-Planter) increased productivity by 8% from 236 to 255 pl PWh^{-1}.

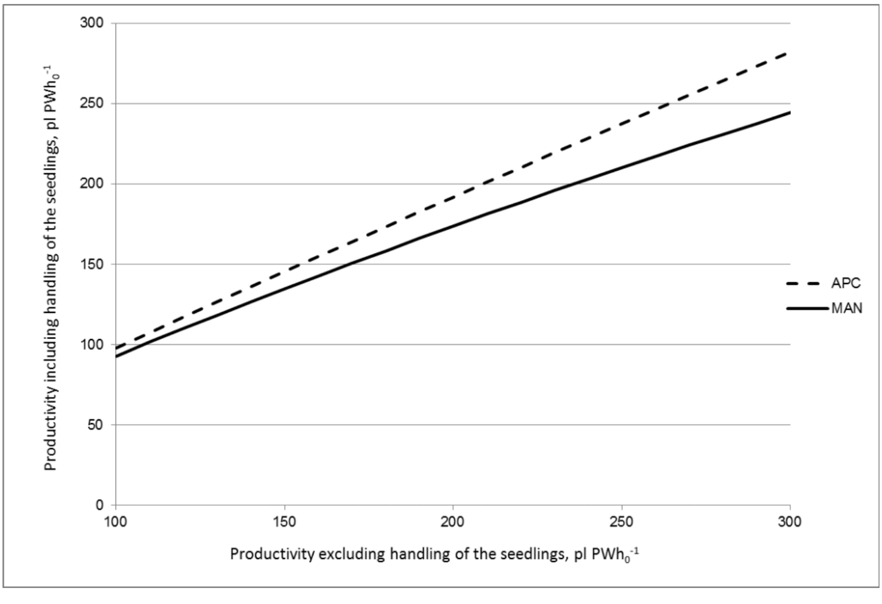

Figure 10. Productivities (pl PWh_0^{-1}) for planting machines with (AUT) and without (MAN) an automatic feeding system when excluding (x-axis) and including (y-axis) the time used for handling the seedlings. Handling the seedlings involves the time spent loading the seedling storage rack (MAN + AUT) and reloading the seedling cassette (MAN). (V).

Finnish Risutec APC planting device with automatic seedling feeding system (196 pl PWh_0^{-1}) had a lower productivity than the Bracke machine (244 pl PWh_0^{-1}), making the unit cost per planted seedling 35.7% higher. The work was interrupted much more frequently with the Risutec APC (4.07 s pl^{-1}) than with the Bracke (0.13 s pl^{-1}), mostly due to problems in the seedling feeding system requiring the operator to stop planting in order to diagnose and solve the problem. However, unit costs for AUT were 4.7% lower than those for Bracke due to higher productivity (281 pl PWh_0^{-1}). (V). The cost-efficiency of the automatic seedling system is highly dependent on mechanical availability as well as additional investment cost (Ersson et al. 2014a).

The cost-efficiency of mechanized planting can be improved by developing machines to enhance productivity. The productivity of machines fitted with single-planting unit has been constant since the mid-1990s, and it appears unlikely that this will significantly change without new or improved technology (Ersson 2014). Multiprocessing, i.e. principle 3 in Harstela's (2004) list is already met as the M-Planter has two mounding and planting units working simultaneously. Based on simulations, more planting units rather than more arms are better for increasing the productivity of excavator-based planting machines working intermittently in Fennoscandian clear-cut sites (Ersson et al. 2013; Ersson et al. 2014b).

Of Harstela's (2004) list, principle 4 (i.e. automatization of work elements) is not met by planting machines in use today. Automation of seedling feeding system was investigated in this dissertation, but for the most part, this aspect of mechanized planting is poorly explored. Solutions should enhance productivity while minimizing the physical and mental strain placed on the operator along with their impact on productivity and quality. Innovations in information, communication, and sensor technology offer new solutions that could be embraced by mechanized planting, although they would likely require additional investment and lead to higher prices and operating costs (Rantala et al. 2009). Thus, the principle of reasonable price in relation to productivity and annual utilization rate (principle 6 in Harstela's list) should be kept in mind when developing new machine concepts. Also, new materials could be embraced in the design of new and existing machines. For example, they could become lighter which could reduce the need of power of the base machine.

Current planting machines must increase their productivity by 100% to compete with the continuously advancing spot mounder followed by manual planting (II), thus improvements to planting machines mainly focus on continuously advancing spot mounders that have the potential for several-fold higher productivity compared to excavator-based spot mounding. Continuous working is principle 5 on Harstela's list, and the Serlachius and Silva Nova were the first continuously working planting machines with high productivity (Kaila 1984; Hallonborg et al. 1995). However, these machines were expensive and only able to perform planting work (Adelsköld 1983, Hallonborg et al. 1995). Building on the lessons learned by Serlachius and Silva Nova, continuously working planting machines should form mounds and be operated by a separate base machine that could be used outside the planting season for other tasks. Saarinen et al. (2013) designed a concept-level continuous working planting machine on a forwarder based on a prototype mounder by Pentin Paja. "Planting tool" was supposed to be based on Serlachius and Silva Nova. They concluded that spot mounding rather than disc-trenching requires a more careful selection of planting spot and stabilization of the machine during planting (Saarinen et al. 2013). The automatic feeding of seedlings would be an essential component for highly productive continuously advancing planting machines. The effective application of automatic seedling feeding systems can lead to cost savings when productivity is sufficiently high and the capital investment of a seedling feeding system is justifiable when productivity and demand are sufficient (V).

In addition to technological advances, mechanization could be enhanced by commercializing the concept more extensively. The development and manufacture of planting machines relies mainly on a small industry performing the majority of work, which has hindered the adoption of mechanical planting work. Hallongren and Rantala (2012) emphasized new ideas and a cooperative enterprise as essential factors in the successful commercialization and implementation of mechanized silviculture. In addition to technological advances, the commercialization of machine concepts must be developed to accelerate mechanization. New ideas and the ability to cooperate are essential success factors in the commercialization of silvicultural products and services. Knowledge of export markets and the means to operate in them are also important (Hallongren and Rantala 2010). Informing NIPFs and forestry professionals about the benefits of mechanized planting (e.g. by organizing work demonstrations) will also facilitate feedback and improve demand as planting machine contractors realize the potential (I).

4.4 Assessment of the research

4.4.1 Validity and reliability

Earlier studies were used as a basis for the cost calculations when studying SQ_1, i.e. the competitiveness of mechanized planting compared to manual planting. However, productivities reported in time studies have been higher, especially for double-unit planting devices (e.g. Rantala et al. 2009; Liepiņš et al. 2011). Skilled operators could reach the productivity required to make mechanized planting cost-effective.

Capital costs were calculated based on new base machines and planting devices (II, V). Sensitivity analyses (Article II; Table 3) showed that base machine purchase price does not markedly affect the competitiveness of mechanized work. In addition, lower capital costs are usually offset by higher maintenance and repair costs and lower technical availability of machinery (Bright 2004). Increasing the capacity utilization of machinery will improve competitiveness.

A follow-up study of M-Planter was restricted to novice operators. None of the operators had used the device before, as M-Planter was introduced to the market for the first time (III). It is also noteworthy that no one had prior experience with organizing the planting work for the M-Planter on a commercial scale. Therefore, the study was a description of the implementation of a new planting device in the operational environment of a planting service provider employing several conractors. The data concerning division of total working time into various time elements was based on the paper forms completed by the operators. Therefore, the reliability of this part of the study relies on the accuracy of the information supplied. Mäkelä (1979) states that there is a risk that operators overestimate their working time, leading to lower productivity figures in follow-up studies such as this one. In any case, to control the reliability, the planting machines were equipped with vibration sensors during the first planting season and the results from the sensors were quite consistent with those obtained from the analysis of the paper forms. However, interruptions including several different tasks were coarse estimates and subsequently divided into separate work elements by the authors.

The video camera proved to be an appropriate data-collection tool in experimental studies, enabling the separation and analysis of very short time elements (IV, V). However, results should be interpreted cautiously due to the small number of observations. Although asked to work normally, there may be an observer effect on operator performance (Mayo 1933). Earlier studies have shown that the productivity of harvester operators may be higher during a study than during unobserved periods (Kuitto et al. 1994; Ryynänen & Rönkkö 2001), and a similar effect has been observed with forwarder operators (Mäkelä 1979).

The regeneration areas represented a typical variety of work difficulty factors that can affect mechanized planting work (III, IV, and V). However, in Articles IV and V, the regeneration areas were selected for the research, meaning that working conditions were similar and ideal for all operators. Observations were thus equivalent and their comparison was more meaningful. Of all the work difficulty factors measured, only surface obstacles (IV) and stoniness (V) affected productivity. Ideal working conditions might explain the relatively high productivity rates observed in experimental studies.

All operators used the M-Planter but the base machine differed so that 13 operators worked with five excavators in Article III, and six operators worked with four excavators in Article IV. Differences in base machines may cause some variation in results, for example the length of the boom might have caused differences in having to relocate base machines with a shorter boom. The size of the base machine has reportedly no significant effect on the productivity of excavator-based planting devices (Arnkil 1997; Rummukainen et al. 2002). Differences between base machines were not statistically significant, and thus the base machine was excluded from the linear mixed models. The influence of the base machine is therefore assumed to be trivial. The Bracke and Risutec planters had different base machines, but base machine costs were assumed to be similar during the cost calculations (V). In reality, the Risutec is a larger and heavier device than Bracke, so it likely requires a larger base machine and thus more fuel to move and operate, which might increase the operating costs and lower its competitiveness.

When studying the automation of a seedling feeding system (SQ_2), the Risutec was assumed to be reliable, as it should be when a new device is introduced to the market (V). However, Risutec APC was a prototype and had not undergone extensive testing or refinement before the study. The performance of Risutec APC was lower than that of the Bracke P11.a, both in terms of productivity and planting quality. The amount of worktime interruptions due to malfunction was high and the time spent repairing the machine would lead to higher unit costs and lower productivity in practice. A machine with a more complex design probably increases the demand for maintenance and repair, which in turn decreases its MA (Mellgren 1989). The added investment cost of the new technology decreases as MA decreases. Ersson et al. (2014a) stated that if MA of the MagMat, an automatic seedling feeding system on Bracke planters, falls by as little as 3% (i.e. from 100% to 97%), the added investment cost must be nearly halved.

The time study provided valuable data and important estimates for cost calculations concerning the operation of the planting device with an automatic seedling feeding system (V). The comparative time study method is reliable, as both operators worked with both machines, not only with the one familiar to them. Because the productivity of Risutec was lower than that of Bracke, an idealized planting machine AUT was used to explore the viability of the automatic feeding of seedlings. The feeding system of the idealized machine was assumed to work continuously rather than utilizing an intermittent process of selecting the seedlings, which is how the Risutec APC performed.

Results concerning the utilization of planting machine capacity (SQ_3) can be considered reliable as only two of the 22 businesses active in 2013 did not fully participate in the survey. The pooled data set represents the entire population of planting machine businesses active in Finland. However, it remains possible that all businesses providing a mechanized planting service were not identified. The questionnaire was extensive and covered the main aspects of mechanized planting, and respondents answered according to their knowledge. However, it should be kept in mind that responses were opinions based on perceptions of their own businesses rather than an objective analysis of accurate data.

Planting work quality (SQ_4) was evaluated by measuring the density of planted seedlings, subjective classification of planting defects, and the quality of mounds formed. Quality could have been measured more precisely to provide high resolution data on the quality of mechanized planting. However, the main focus was on productivity and previous studies have examined quality of mechanized planting (Saarinen 2006; Rantala et al. 2009; Ersson and Petersson 2011; Luoranen et al. 2011; Ersson and Petersson 2013) and these measures were not taken. Nevertheless, quality is an important factor to consider, as clients may not be willing to pay for faster but lower quality work. Ultimately, a successful regeneration result ensures that high quality wood is available in the future.

4.4.2 Generalization of results

A good description was provided of the costs of mechanized planting with either single- or double-unit planting devices compared to manual planting (SQ_1). However, cost calculations are only indicative results generated by given assumptions, and thus generalization of the results should be made carefully. The various ways in which different issues affect cost-competitiveness were shown, as were the conditions under which mechanized planting work would be cost-competitive compared to manual planting.

The main features of working with the M-Planter planting device in practice and experimental conditions were illustrated. Because the M-Planter has two separate planting units, results cannot directly be generalized to other devices fitted with a single-planting unit. A study of M-Planter working in practice described the implementation of the new planting device in the operational environment of a service provider employing several planting businesses (III). Productivity of novice operators was investigated in terms of total worktime distributions. However, the share of the total time for relocations might be an underestimate because of the difficulties in gaining information on relocations provided by separate persons. The same problem might affect information concerning maintenance and repair times which may be greater than results show. The experimental study of the M-Planter focused on productive worktime, which is only part of the total worktime (IV). Due to a small number of observations, results of the study should be interpreted carefully.

When studying the automation of a seedling feeding system (SQ_2), it is prudent to recall that Risutec APC is a prototype and results cannot be generalized to other planting devices with automatic seedling feeding systems (V). However, AUT was used to illustrate the potential and importance of the automatic seedling feeding system for future planting devices.

Given that all businesses providing mechanized planting in Finland in 2013 were interviewed, an accurate and detailed survey of the utilization and capacity of mechanized planting (SQ_3) was formed (I).

Regeneration areas planted represented the typical variety of worksites in Nordic countries, presenting work difficulty factors that affect productivity and quality of mechanized planting work (III, IV, and V). On the basis of these studies, the quality of mechanized planting can be considered good (SQ_4).

Field experiments were short-term trials and this limits the generalization of results. Other approaches could have been used to yield other forms of data, e.g. simulation studies.

Simulation is: “the imitation of the operation of a real-world process or system over time” (Banks 1998). For example, in Article V the operation of the Risutec APC could have been simulated. Simulation would have enabled an examination of performance over longer time periods and under different economic circumstances, as well as explore new machine designs without having to build them. Field data could have provided an accurate basis on which to develop and test the simulations.

4.4 Recommendations for future research

To accurately determine the cost of mechanized tree planting, work supervision should also be included in the cost calculations. Mechanized planting combines two work tasks, mounding and planting, and both can be supervised simultaneously by a single supervisor, which probably improves the cost-competitiveness of mechanized tree planting compared to manual methods. Also, the entire seedling supply chain from production to worksite should be developed to better meet the needs of mechanized planting. Ersson et al. (2011) showed that investments in specific packaging systems for current planting machines are justified only when their productivity and demand increases substantially from today’s levels. In the future, when reliable planting devices with automatic seedling feeding systems are available, tray-wise loading combined with de-plugging seedlings from cultivation trays would be the most efficient method for loading and feeding the seedlings (Ersson et al. 2014a). Optimization and integration of the entire mechanized planting chain from nursery to outplanting could lower the cost of mechanized planting.

Earlier studies have handled the quality of mechanized planting (e.g. Luoranen et al. 2011), but comparing the growth of seedlings and costs in mechanized planting, combining two work tasks compared to separate soil preparation and manual planting, would be interesting. Usually some time remains between mounding and manual planting, and during this time only unwanted tree species that disturb the development of future coniferous crop trees are growing in the regeneration areas. Thus, mechanized planting most probably brings some advantages for both seedling growth and total costs when observing the early development of Norway spruce stands.

A need exists for developing planting machines with several-fold higher productivities compared to machines currently used, as shown in chapter 4.3. Besides developing completely new machine concepts, machines in use today could also be improved.

Principle two of Harstela’s (2004) list is satisfied as the planting machines in use today perform soil preparation and planting in sequence. However, enabling additional work tasks such as irrigation, fertilization, or spatial information to the same machine could add value and make mechanized planting more effective and should be investigated. Irrigation is probably not needed in Finland when mounding is used as a soil preparation method, but there might be such a need when reforesting plantations in tropical regions. The aim of forest fertilization is to improve the growth of a tree stand by adding nutrients, the lack of which limits growth. For example, growth disturbances have been encountered in eastern Finland in fertile spruce stands, which may be induced by an imbalance in nutrient status, particularly a deficiency of boron in relation to nitrogen that could be avoided by appropriate fertilization (Saarsalmi and Mälkönen 2001). Real-time spatial information could ensure automatic quality control, as it shows the number and exact location of planted seedlings. Such equipment would increase the cost-efficiency of the mechanized planting work compared to manual planting.

5 CONCLUSIONS

Harstela (2004) described the fundamentals of mechanization (chapter 1.3), from which 1, 4, 7, and 8 were investigated in this thesis. Specific research questions (SQs) were formulated according to these principles of techno-economically reasonable mechanization (Harstela 2004). The SQs were answered as follow:

- SQ_1: The productivity of mechanized planting is higher than that of manual planting, but the work is currently not economically competitive compared to manual planting. However, increased efficiency through the use of skilled operators and worksite selection can lower mechanized planting costs below those of excavator spot mounding followed by manual planting. (Principle 1)

- SQ_2: Increasing productivity and thus reducing operating costs with an effective automatic seedling feeding system remains possible, although Risutec APC was not yet sufficiently developed to achieve this goal. (Principle 4)

- SQ_3: Planting machine capacity is underutilized and could be improved to enhance productivity and cost-efficiency. Technical availability of the machines is good. (Principle 7)

- SQ_4: The quality of mechanized planting work is good. (Principle 8)

The results of this thesis showed that principles 1 and 8 are satisfied and principles 4 and 7 require confirmation is practice. In the future, attention should be paid to automation and continuous working (principles 4 and 5) as they have the potential to increase productivity of mechanized planting substantially. However, when developing continuously advancing automated planting machines, principles 6 and 7 should be kept in mind as the cost of complex machinery can exceed any practical benefits and is more vulnerable to malfunction.

Based on the results here, other evidence and practical experience, for mechanized planting to be cost-efficient the following essentials are required:

- *Technical reliability of the machine.*
  Besides machines being reliable, their capacity should be used efficiently.

- *High skill of machine operator.*
  The operator is a key factor affecting the productivity of machine work, thus ensuring the proper training in operation is extremely important. Also, operators skilled at operating the base machine typically learned to use the planting device quicker and more effectively.

- *Worksite selection.*
  Worksite stoniness should be low, and the harvesting of slash and stumps improves working conditions. Increasing the worksite area and making machine relocations more efficient could also increase the productivity of mechanized

planting. The introduction of work supervisorss to help select suitable planting locations is essential.

- *Quality, availability, and logistics of seedling supply.*
  To ensure successful planting, the seedling material should be high quality and prepared for the intended planting period. Improving the care of seedlings during transport and temporary storage could increase the productivity of mechanized planting.

This dissertation concludes that the opportunity exists for mechanized tree planting to be more effective than manual methods. Mechanization requires much more than the construction of a cost-efficient machine. For tree planting machines to be economically competitive, the results suggest that worksites must be carefully evaluated and planted by skilled operators applying appropriate machines that accommodate and respond to the factors influencing productivity and thus maximizing cost-efficiency. Increasing productivity and thus reducing operating costs by mechanization of the planting work remains possible, especially in the future when more improved technology becomes available. Also, the optimization and integration of the entire mechanized planting chain from the nursery to outplanting is of critical importance.

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