Aspects of Automation of Selective Cleaning

Karin Vestlund
Faculty of Forest Sciences
Department of Silviculture
Uppsala/Umeå

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Abstract

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Cleaning (pre-commercial thinning) is a silvicultural operation, primarily used to improve growing conditions of remaining trees in young stands (*ca.* 3 - 5 m of height). Cleaning costs are considered high in Sweden and the work is laborious. Selective cleaning with autonomous artificial agents (robots) may rationalise the work, but requires new knowledge. This thesis aims to analyse key issues regarding automation of cleaning; suggesting general solutions and focusing on automatic selection of main-stems. The essential requests put on cleaning robots are to render acceptable results and to be cost competitive. They must be safe and be able to operate independently and unattended for several hours in a dynamic and non-deterministic environment. Machine vision, radar, and laser scanners are promising techniques for obstacle avoidance, tree identification, and tool control. Horizontal laser scannings were made, demonstrating the possibility to find stems and make estimations regarding their height and diameter. Knowledge regarding stem selections was retrieved through qualitative interviews with persons performing cleaning. They consider similar attributes of trees, and these findings and current cleaning manuals were used in combination with a field inventory in the development of a decision support system (DSS). The DSS selects stems by the attributes species, position, diameter, and damage. It was used to run computer-based simulations in a variety of young forests. A general follow-up showed that the DSS produced acceptable results. The DSS was further evaluated by comparing its selections with those made by experienced cleaners, and by a test in which laymen performed cleanings following the system. The DSS seems to be useful and flexible, since it can be adjusted in accordance with the cleaners' results. The laymen's results implied that the DSS is robust and that it could be used as a training tool. Using the DSS in automatic, or semi-automatic, cleaning operations should be possible if and when selected attributes can be automatically perceived. A suitable base-machine and thorough research, regarding *e.g.* safety, obstacle avoidance, and target identification, is needed to develop competitive robots. However, using the DSS as a training-tool for inexperienced cleaners could be an interesting option as of today.

Key words: autonomous off-road vehicle, decision support system, interviews, robot, pre-commercial thinning, simulations, training-tool.

Author's address: Karin Vestlund, Department of Silviculture, Swedish University of Agricultural Sciences, P.O. Box 7060, SE-750 07 UPPSALA, Sweden.
E-mail: Karin.Vestlund@ssko.slu.se

" Fremtiden kommer af sig selv, det gør fremskridtet ikke."
Poul Henningsen

Contents

Appendix

Papers I-V

This thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Vestlund, K. & Hellström, T. Requirements and system design for a robot performing selective cleaning in young forest stands. (Accepted for publication in Journal of Terramechanics).

II. Vestlund, K. 2004. Assessing rules and ideas for stem selection in cleaning. Baltic Forestry, 10(2): 61-71.

III. Vestlund, K., Nordfjell, T., Eliasson, L. & Karlsson, A. A decision support system for selective cleaning. (Submitted).

IV. Vestlund, K., Nordfjell, T. & Eliasson, L. Comparison of human and computer-based selective cleaning. (Submitted).

V. Erikson, M. & Vestlund, K. 2003. Finding tree-stems in laser range images of young mixed stands to perform selective cleaning. In: Hyyppä, J., Naesset, E., Olsson, H., Granqvist-Pahlén, T. & Reese, H. (Eds.) Proceedings of the Scandlaser scientific workshop on airborne laser scanning of forests. Working paper 112, Department of Forest Resource, Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden. p. 244-250. ISSN: 1401-1204.

Introduction

The forest is valuable for Sweden as a whole. In 2003 the export value of forest and forest industry products was 109 billion SEK, which was 13% of Sweden's total export value (Anon. 2004a). Thus, it is important to have progress in all aspects of forestry.

Since 1905, it has been compulsory in Sweden to reforest harvested areas (Holmberg 2005). The common silvicultural practice from the late 1950s has been a sequence of clear-cutting followed by site-preparation, planting or natural regeneration, and then tending of the stand during the whole rotation period until a new harvest can be performed, *i.e.* even-age management. Standard tending operations in Swedish forests include cleaning (pre-commercial thinning) and thinning (commercial thinning) (*cf.* Anon. 2004a).

Cleaning

Cleaning is performed in young forest stands, prior to thinnings, in Nordic countries usually when the stand is *ca.* three to five meters of height (Varmola & Salminen 2004). The National Board of Forestry defines cleaning as the thinning of a stand, in which the main part of the cut volume originates from stems of less than 10 cm in diameter at breast height (Pettersson & Bäcke 1998). In dense stands a reduction in the number of stems increases the volume growth per stem (Aussenac & Granier 1988, Pettersson 1993), as the remaining trees (main-stems) can benefit from increased access to nutrients, water, and light (Eriksson 1976).

The most common reason (the broad objective) for performing cleanings mentioned in Sweden is economic; concerning increased revenue later in the rotation period (Berg *et al.* 1973) and/or reduced future silvicultural costs (Håkansson & Steffen 1994). To achieve the broad-objective usual sub-objectives of cleaning are to produce more volume per stem, to produce stems with certain characteristics, and to minimise the operational costs. Thus compromises between sub-objectives might be needed if/when improvement for one sub-objective only can be accomplished at the expense of another (*cf.* Keeney & Raiffa 1993).

The lower the height and the lower the number of stems per hectare the faster cleanings can be performed (Bergstrand *et al.* 1986), so cleaning young stands should be cheaper than cleaning older stands. However, premature cleanings can have disadvantageous effects, such as rank-growth of trees (causing *e.g.* thick branches) or establishment of sprouts causing a new demand for cleaning (Eriksson 1976, Andersson 1985). Postponed cleanings can result in over-dense stands, with high risks for damage by snow, insects, wind *etc.* (Eriksson 1976). Furthermore, no or very low-intensity* cleanings increase the share of early

* **Intensity**, high intensity means that many stems in the stand are cut, low intensity the opposite.

thinnings with a negative revenue and the risk of getting a lower income over the whole rotation-period because the growth is divided on a large number of stems (Frohm 1996). Cleaning manuals state that the operation should be performed when there is a risk that potential main-stems will be adversely affected by competition and/or damaged (*cf.* Karlsson *et al.* 1997). Cleaning manuals for coniferous (Scots pine and Norway spruce) stands in Sweden of which the average height is some three meters state that, depending on site quality and species, between 1 400 and 4 000 stems per hectare should remain (*e.g.* Pettersson & Bäcke 1998, Anon. 1999a, Normark & Bergqvist 2000). In Finland and Norway the recommended spacing after cleaning of Scots pine stands varies from 2 000 to 3 500 stems per hectare (Varmola & Salminen 2004).

Cleaning operations can be selective, geometrical, or a combination of both (Berg *et al.* 1973). Geometrical cleaning can be cheaper than selective cleaning in stands with at least 10-20 000 stems per hectare (Fryk 1985, Ryans 1988, Bergkvist & Nordén 2004). Reasons for making individual selections include a desire to improve stand quality and/or influence species composition, which might increase the final profitability (*e.g.* Berg *et al.* 1973). Selective cleaning is frequently used today in many parts of the world (*cf.* Anon. 1999b, Kaivola 1996, Strobl & Bell 2000, Ek 2003, Ladrach 2004). Geometrical cleaning, in strip, checkerboard, or other patterns, is common in loblolly pine (Pinus taeda L.) stands in USA (Lloyd & Waldrop 1999) and also used in Canada (Ryans 1988, Ryans & St-Amour 1996) and in dense natural generations of beech in Denmark (Möller-Madsen & Petersen 2002). Chemical cleaning can be an inexpensive approach for reducing the amount of deciduous stems, but it is not widely used due to its environmental affects. However, herbicides are used in some 35% of the treated area in Canada (Ryans & St-Amour 1996, Anon. 2004b).

Consequently, it is generally difficult to make decisions such as when and how to clean, see also the section *Automatic selective cleaning*.

Development of forestry operations in Sweden

Forestry has undergone considerable changes in the Nordic countries during the last century, from a labour intensive to a capital-intensive business. In the late 19th century, the industrial revolution reached Swedish forests and along the riverbanks and the coastline sawmills and later on pulp mills were established. This was by reason of the demand for sawn timber in Europe. The forest operations at that time were highly seasonal; the round wood was harvested during the winter with axes and saws, and transported to rivers or lakes by horse-drawn sleighs (Kardell 2004). The transportation of logs to the mills took place in the spring as the rivers were used for floating the logs downstream. Cleaning was introduced into Swedish forestry during this century using manual tools like brash hooks, special shears, axes, saws and knifes (Björkman 1877, Wahlgren 1914).

The idea for using mechanical aids for harvesting was initiated in the early 20th century in Sweden, and power-saws were introduced for military purposes in 1931 and in company owned forests by 1936 (Carpelan 1948). In the middle of the 1950s most harvesting was performed with power-saws (Andersson 1986) and motor-manual brush saws for cleaning were introduced (Nordansjö 1988). In the 1950s chemical treatments (herbicides) also came into use to control deciduous trees as this method only cost 25% of the manual methods (Rennerfelt 1948, Häggström 1955, Kardell 2004). As the use of forest products increased, tending the forest became more important (Kardell 2004). Cleaning has been a common practice in Swedish forests since the 1950s (Fig. 1) (*cf.* Anon. 2004a).

Progress in transport and harvesting techniques continued. The introduction of hydraulic cranes for loading in the beginning of the 1960s, enlargement of the forest road network, and the expansion of waterpower in the rivers changed long distance transportation in favour of trucks (*cf.* Nordansjö 1988). During the 1960s forwarders were introduced, in 1973 the first complete harvester appeared on the market and gradually the forest workers became machine operators (Andersson 1986, Nordansjö 1988). Motor-manual brush saws were still in use, although the saws, the work practices, and the work organisation were improved (*cf.* Pettersson 1973). During the 1970s the use of chemical cleaning was under discussion (Ahlén 1971) and it was prohibited in 1984 (Fig. 1) (Anon. 1985).

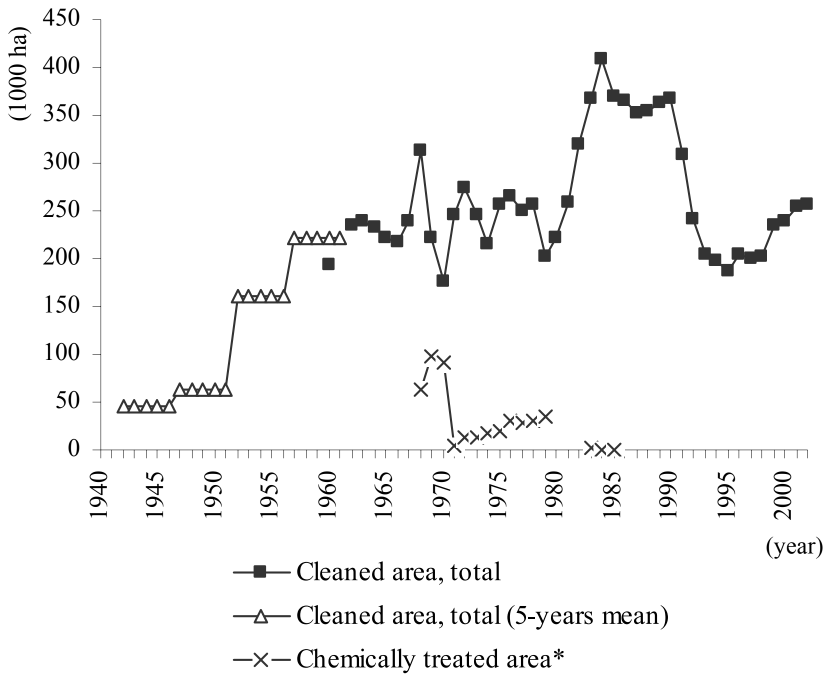

Figure 1. Total cleaned area in Sweden according to the National Board of Forestry from 1942 to 2002. The area treated during 1942-1961 is presented as 5-years mean values (Vestlund 2001a, Anon. 2004a). * = Chemically treated area was estimated by means of sales during the years 1968-75 (Anon. 1978). The figure for 1976 is the announced area and the presented figures 1977-79 and 1983-85 are the actual area treated with chemicals (Anon. 1979, Anon. 1987). *N.B.* 1980-82 no area was chemically treated.

Attempts to mechanise cleaning were started in Sweden in the 1970s (Berg *et al.* 1973, Gustavsson & Moberg 1975). A shortage of persons performing cleaning and the ban of herbicides created a cleaning backlog in the beginning of the 1980s (Mellström & Thorsén 1981). Hence, in the late 1980s and beginning of the 1990s some cleanings in industrial forests were performed mechanically (Myhrman 1987, Mattsson & Westerberg 1992). Lindman (1987) found that mechanical cleaning was cheaper than motor-manual cleaning in stands with more than 10 000 stems per hectare before cleaning. However, no more than 20 machines were said to be in use annually during these years (Mattsson & Westerberg 1992, Lidén 1995). The total economy for the machines was poor and it became easier to find persons performing cleaning. These are the principal reasons for the negligible amount of mechanical cleaning today (Ligné 1999). Currently nearly all cleanings in Europe are done with motor-manual brush saws (Ligné 2004).

Motor-manual felling with chainsaws disappeared from large-scale forestry during the 1990s (Lidén 1995, Synwoldt 2001). The harvesting machines and the logistics have been refined, cutting both the time and cost required to deliver round wood to the industrial sites. Unmanned harvesters, in which the forwarder-driver uses a remote control to perform the harvesting are already available, but as the harvester and forwarder cannot operate simultaneously the benefits decreases (Jansson 2001, Thorner 2004). Cleaning, on the other hand, has not progressed in the same way. The average cost for cleaning has increased during the last twenty years compared with logging and regeneration costs (Ligné 2004). Furthermore, the nominal cost per hectare has remained fairly constant since 1990 (Anon. 1992, Anon. 1998, Anon. 1999c, Anon. 2004a), and motor-manual work is laborious. These may be the reasons why, once again, it is difficult to find cleaners in Sweden (Vestlund 2001b). This has made some cleaning entrepreneurs look for personnel from low-wage countries such as Poland, Russia, and the Baltic States; and there have also been cases where dishonest persons have received payment without fulfilling their cleaning contracts (*ibid.*). In Canada too, there are concerns that there will be a lack of cleaners and that costs of cleaning will rise (Anon. 2001a, St-Amour 2004). From the mid-1980s to the late 1990s the intensity of cleanings diminished in Sweden and since 1994 it has become more common to postpone the operation (Nilsson & Gustafsson 1999). A revised Forestry Act came into practice in Sweden in 1994 which deregulated cleaning of stands over 1.3 m of height (Pettersson & Bäcke 1998). There seems to be an unwillingness to invest in the early stage of the rotation-period, even though cleaning has proved to be profitable (*cf.* Berg *et al.* 1973, Cain & Shelton 2003, Tong *et al.* 2005), when cleaning no longer is compulsory. This has led to a renewed interest in mechanised cleaning (*e.g.* Glöde & Bergkvist 2003, Ligné 2004).

Autonomous unmanned machinery

Initial ideas regarding the automation of forest operations were presented at the Swedish University of Agricultural Sciences (SLU) in 1994-95 (Gellerstedt 1995), and a course called "Robotics with applications to forestry operations" was held, at which a Canadian project for developing robots for cleaning (weeding, brushing and thinning in young coniferous stands) was presented. In this project some prototypes were built, designed to develop and demonstrate autonomous[†] control, to study forest environment sensing, and to test mobility concepts (Kourtz 1996). The project started in 1993 but ended, due to lack of funding, in 1995 (*ibid.*). In the following years some initial studies regarding autonomous cleaning were made at SLU (Gellerstedt *et al.* 1999).

The number of other projects that have considered mobile autonomous artificial agents (robots) for forestry operations seems to be limited. Kurabyashi & Asaman (2001) have developed a tracked robot for removing bushes between desired trees in steep terrain, where the desired trees are identified with tags. Canning *et al.* (2004) presented a small test vehicle with shaft encoders and ultrasonic sensors that autonomously navigated down a 150m forest path. There is also an ongoing project called: Autonomous Navigation for Forest Machines, which started in 2002 and is a part of a long-term vision to develop an unmanned vehicle that transports timber from the felling area to the roadside, and addresses the problems associated with localisation and obstacle avoidance in forest terrain (Hellström 2002, Hellström *et al.* 2005). However, research and development regarding autonomous land vehicles for use in other industries can benefit the forestry sector. Interesting studies have for example been made for use in agriculture in recent decades (*e.g.* Tillett 1991, Marchant *et al.* 1997, Noguchi *et al.* 1998, Zhang *et al.* 1999, Wilson 2000, Have 2002). The agricultural activities addressed have included harvesting, mowing, weed control, and applications of pesticides.

Safety is the most important issue in developing automatic unmanned vehicles, along with reliability, and the unstructured outdoor environment makes it challenging to reach acceptable reliability and safety levels (Tillett 1991). However, recent development in computer vision and global positioning system (GPS) make such sensors interesting for automatic guidance of agricultural vehicles, especially if data from those two sensor-types could be combined (Keicher & Seufert 2000, Wilson 2000). Durrant-Whyte (2001) states that the necessary sensors, algorithms and methods to develop and demonstrate an operationally viable all-terrain autonomous vehicle already exist. Declining prices for computer power, machine vision, and navigation systems also favour the development of autonomous outdoor vehicles (Keicher & Seufert 2000). Although, most work in this area is at the pre-commercial stage, except for lawnmowers (Nielsen & Fountas 2002).

Automatic selective cleaning

The cleaning results should not be affected if the operation is automated. Consequently, in selective cleaning decisions must be made for each stem, either it

[†] **Autonomous** refers to something that is independent of others, acting or able to act in accordance with rules and principles of one's own choosing, from the Greek word autonomos, living under one's own law (Anon. 1995a). An autonomous robot can adapt to changes in its environment or in itself and continue to reach its goals (*cf.* Russell & Norvig 1995), see also the section *Decision Support Systems* below.

is a main-stem or it is not, and automating the decision process requires a computer-based program, *e.g.* a decision support system (DSS).

Optimal decisions

The mathematical aspects of decision theory usually concern optimisation under constraints. Typical constraints are economical, time or labour. When modelling a decision problem Boman & Ekenberg (1999) states that one has to:

- Compare alternatives with respect to different perspectives, *e.g.* environmental, financial, security
- Compare alternatives within each perspective
- Estimate the probabilities that the given status occur, given that a certain act is performed
- Estimate the value of the consequences

An optimal decision requires that the expected utility for each course of action can be calculated (*cf.* Boman & Ekenberg 1999).

Stem selection in forestry

To perform an optimal cleaning each stem has to be given an explicit grade in comparison to all other stems, which determines if the stem is a main-stem. However, it is not possible to reliably predict the outcome of a decision to select a certain stem since it cannot be known in advance how this stem will develop in the complex forest ecosystem, *i.e.* in its interactions with soil, micro organisms, microclimate, plants, animals *etc*. (*cf.* Allen & Gould 1986, Mendoza & Sprouse 1989, Gadow & Füldner 1995). Forestry decisions also often concern long time horizons and multiple stakeholders with separate interests, which further complicates the decision-making (*cf.* Kangas & Kangas 2004). There are, for example, uncertainties regarding how stands will develop after thinning operations (Gadow & Füldner 1995) as well as regarding which tree qualities that will be desired over time. Furthermore, the motives for owning a forest vary (*cf.* Menger 1934, Hugosson & Ingemarsson 2004) and accordingly the silvicultural goals of different forest owners. Thus, the decision situation in a stand can be characterised by a lack of information and be classed as uncertain, *i.e.* each action has several possible outcomes for which the probabilities are unknown (Siddall 1972).

Nevertheless, to be able to make individual selections in practice, each stem must be differentiated by some of its characteristics. To be useful to the decision maker, the characteristics should be both comprehensive and measurable (Keeney & Raiffa 1993). In the decision-making process a cleaner is limited to use the available instructions and information, what he sees, what he has learned, and what he remembers from the previous selections. Kahn (1995) states that decisions made during thinning are partly based on subjective criteria and partly on indistinct instructions, and the selections are made using ocular estimations and not exact measurements (Daume *et al.* 1997). Cleaning decisions are also dynamic in the sense that they must be redefined in the face of changing information (*cf.*

Ducey 2001). When one stem is removed, the competition might change and the necessity to remove other nearby stems might disappear (Kahn 1995).

People solve uncertain, ill-structured, problems by the shrewd use of heuristics and at the expense of giving up guaranteed completeness of searches and optimality of the solutions attained (Simon 1995). The solutions applied when solving complex and uncertain decisions are generally good or bad, rather than true or false (*cf.* Allen & Gould 1986, Gadow & Füldner 1995). To automate the selection of main-stems, computer-based decisions must render acceptable cleaning results. It is not necessary to find the best solution, but to quickly find a sufficiently good one (*cf.* Daume & Robertson 2000a). Mendoza & Sprouce (1989) replaced the traditional view of optimising the attainment of a given objective with a more practical concept of "satisficing" or attaining a satisfactory level of achievement.

Decision Support Systems

Decision Support Systems (DSSs) are computer-based systems designed to represent and process knowledge in order to support decision-making activities (*cf.* Holsapple & Whinston 1996). DSS is a broad term and its definition varies, it does not necessarily include artificial intelligence (AI), but DSSs are often used for complex decision-making (*cf.* Druzdzel & Flynn 2000). AI is that field of computer usage which attempts to construct computational mechanisms for activities that are considered to require intelligence when performed by humans (Partridge 1998). It is also the field of research of human thought processes, to understand what intelligence is. Thus, AI is both a part of computer science and a part of psychology and cognitive science (Simon 1995). AI applications can be either stand-alone software, such as decision support software, or embedded in robots.

Expert systems and Knowledge-based (KB) systems are a kind of DSSs that support the decision-making process in a narrow well-defined area using AI techniques to store and retrieve knowledge and consist of both data and relationships among the data (Mills 1987). Other fields of AI include natural language processing, knowledge representation, machine learning, automatic programming, and pattern recognition (Holsapple & Whinston 1996).

The terms expert systems and KB systems are usually used synonymously (Mills 1987, Holsapple & Whinston 1996). However, expert systems usually perform tasks which normally require a human expert and can involve heuristics, while the term KB systems can also be used when tasks that require detailed knowledge, but not a human expert, are performed (Mills 1987). The two main components of an expert/KB system are the knowledge base, which differs from a database in that it contains executable program code (instructions) and the inference engine, which interprets and evaluates facts, instructions and data in the knowledge base (Waterman 1985).

Thus, automatic selections of stems need some kind of a DSS and that certain characteristics of the stems can be perceived. To develop a cleaning DSS, appropriate objectives for the cleaning must be defined and an appropriate set of attributes and/or rules should be associated to them (*cf.* Keeney & Raiffa 1993). However, incorrect decisions can be caused by three kinds of errors (Giarratano & Riley 1998, Daume & Robertson 2000b):

- Too few attributes are used
- Wrong attributes are used
- Unsuitable interference of attributes

A cleaning DSS should include as many attributes (and rules) as needed to give acceptable result, but as few as possible to make the system simple and fast (*cf.* Daume & Robertson 2000a).

Objectives

The aim of this thesis was to analyse key issues regarding automation of cleaning; suggesting general solutions and focusing on automatic selection of main-stems.

The objectives of Paper I were to assess forestry requirements (mainly from a Nordic perspective), review available technology, and to suggest a system design for a robot performing selective cleaning in young forest stands. The objective of Paper V was to test if laser scanning could be a possible sensor technique for finding stems in young forest stands.

The objective of Paper II was to assess the explicit and implicit "rules" and ideas used in cleaning in order to facilitate the development of a DSS for selective cleaning. The objectives of Paper III were to develop a DSS for automation of individual stem selections in practical cleaning and to test if it could render acceptable results. Further evaluations of the DSS were made in Paper IV, where the objectives were to compare the cleaning results of experienced cleaners and DSS simulations when "similar" instructions were given, and to assess the usefulness and robustness of the DSS.

Material and methods

Review

A review was made to analyse the requirements a cleaning robot must meet. Cleaning manuals/instructions, as well as literature regarding mechanised cleaning, forest machines, cleaning-stands, and forest terrain were used to describe typical requests, focusing on Swedish conditions (Paper I and partly used in Paper II). Literature regarding various sensors and localisation techniques, especially for outdoor applications, were used to identify possible solutions to meet the stated requirements. Literature about the detection, identification and classification of trees, path planning, and forest machinery were also used to introduce promising ideas and techniques that could fulfil the stated requirements. (Paper I).

Interviews

Qualitative interviews were made with thirteen cleaners in 2001 using a semi-structured approach (Patton 1990). The interviewed cleaners, all men, worked in central Sweden and were either entrepreneurs themselves (5) or employed by an entrepreneur (8). Most of their commissions were obtained from industrial forest owners, but some also worked for non-industrial private forest owners (NIPF owners). The cleaners had varying degrees of experience, and the ten cleaners with more than two years cleaning practice were referred to as experienced cleaners. All interviews were taped and then transcribed. The statements the interviewees made mostly concerned themselves, but in a few cases they referred to other cleaners, or cleaners as a group. The interviews concerned:

- Work organisation/situation
- Instructions given to cleaners
- Preferred characteristics of main-stems
- Practical selection
- Difficulties
- Foundations of cleaning knowledge/experience

When the interviewees' answers gave no further information, *i.e.* when saturation was achieved (Glaser & Strauss 1967), interesting information was clustered and checked for similarities or disagreements. The findings were complementary and no real discrepancies appeared, so the results were presented as a generalised image, a gestalt (Eisner 1998). From this gestalt, further abstractions were made. (Paper II).

The Decision Support System

The abstracted results from the interviews were compared with the literature regarding cleaning instructions, also used in the review, and the conclusions from these comparisons were used to form a set of basic rules for selective cleaning (Paper II).

A DSS was developed, and the restrictions and attributes included in it were evaluated and improved (*cf.* Vestlund 2003) in accordance with the variables currently used for representing acceptable cleaning results (presented in Paper II), *i.e.* the number of stems per hectare, species composition, and percentage of damaged stems. Restrictions for minimum and maximum distances between stems were also included.

The DSS uses three parameters, three thresholds and a "quality criteria" definition regarding species, diameter, and damage, for selecting main-stems. Four types of damage were used to define damage (see section *Field inventory*) and the preferred diameter was expressed as area and species specific ranges. The three parameters depend on the purpose of the cleaning. The first parameter is the requested spacing, and concerns the density target and the maximum distance restriction. The squared double-spacing is used to divide the area to be cleaned into smaller parts, here called sections. To reach the density target each section should have four remaining stems, on average, after cleaning. The second parameter is the minimum allowed distance between two stems. This parameter causes the DSS to reject stems if they are situated within this distance from an already selected main-stem. The last parameter is the requested percentage of deciduous stems, and influences the final selection of remaining stems.

In areas where there are too few stems that fulfil the "quality criteria" to reach the density target more stems can be selectable according to two thresholds. Roughly speaking, the first threshold regards undamaged stems that do not fulfil the "quality criteria" and the second regards damaged stems. The third threshold influences the final selection of remaining stems, and could allow the selection of more, than the average number of four, stems in an area.

The selections rest upon accessible inputs, *i.e.* data from the current and previous sections, and selections that have already been made are not changed. A decision to save a stem affects forthcoming decisions, especially in surrounding sections, in order to meet the requested over-all targets for the stand. (Paper III).

Field inventory

A field inventory (FI) was conducted in the summers of 2002 and 2003 at two areas near Enköping, two near Skutskär, and two near Jönköping (Fig. 2). The selected areas (Table 1), were in need of cleaning according to cleaning manuals (*cf.* Anon. 1999a) and the target was to leave approximately 2 500 stems per hectare after cleaning.

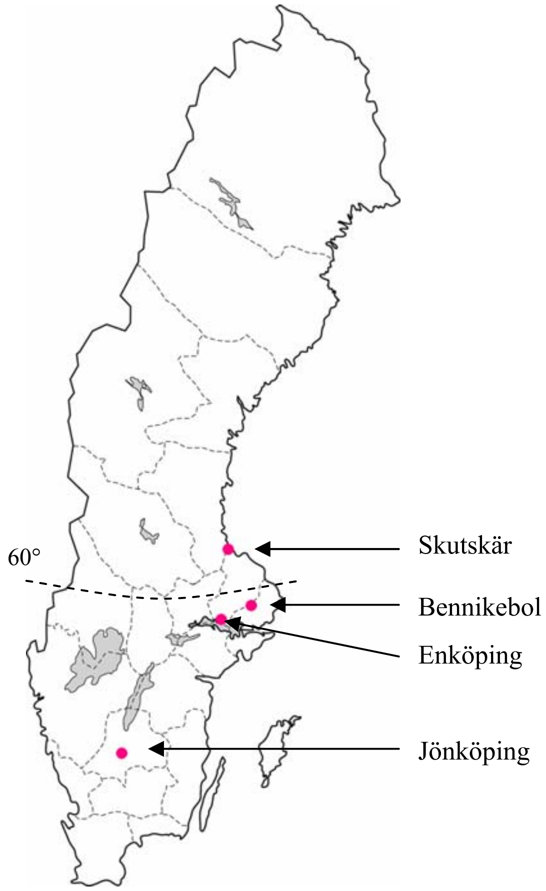

Figure 2. Sweden, location of the field inventory areas (Skutskär, Enköping, and Jönköping) and the place where the laser scanning was performed (Bennikebol), see section *Laser scanning*. The position of the 60th parallel is roughly marked.

The inventoried area was 160 m^2 at each location, except the JönköpingPine-area, where it was 224 m^2. Retrieved characteristics were: diameter, position, species, and damage. All stems over one cm in diameter at breast height (dbh) were callipered with mm precision. The centre positions of the stems were measured in X and Y-planes at breast height with cm precision. The stems were categorised as Scots pine (Pinus sylvestris L.), Norway spruce (Picea abies (L.) H. Karst), juniper (Juniperus communis L.), birch (Betula pendula Roth and Betula pubescens Ehrh.; species not separated), or other deciduous. Four damage types, considered automatically measurable, were chosen for defining damage:

1. Double top, where the height of the shorter top was at least 0.5 m and at least 75% of the height of the taller top
2. Leaning stems, *i.e.* stems having a mean inclination angle larger than 2° from root to top
3. Stems with crooks, where it was not possible to join the centres of each end with a straight line without crossing the outer edges of the stem at any point

4. Stem damage with an area larger than the squared radius at breast height (r^2) of the stem.

Stems with damage of types other than those defined were noted as having "undefined damage".

Table 1. Stand data from the field inventory (*cf.* Fig. 2), all stems over 1 cm in diameter at breast height, dbh, were counted and measured

	Location					
Stand data	Enköping Pine1	Enköping Pine2	Jönköping Pine	Jönköping Spruce	Skutskär Pine	Skutskär Spruce
Density (stems per ha)	10000	9875	5893	5500	6188	6938
Proportion of birch stems (%)	52	33	60	8	2	19
Proportion of "other deciduous" stems (%)	4	1	0	0	2	36
Proportion of stems with damage (%)	58	41	65	16	14	60
Proportion of stems with "undefined damage" (%)	4	1	8	7	5	5
Mean dbh, total (mm)	30	29	40	46	69	36
Mean dbh, coniferous (mm)	42	34	72	47	70	50
Mean dbh, deciduous (mm)	20	19	18	41	30	24

(Papers III and IV).

Simulations

The DSS was used for a total of seven computer-based cleanings, *i.e.* simulations.

Firstly, six cleaning simulations with different settings were run (Paper III):

- General
- Reverse
- Changed thresholds
- 4000-stems
- Increased minimum distance
- 30%-deciduous

The "General" simulation was run in accordance with instructions generally given to cleaners (presented in Paper II). The density target was set to 2 500 stems per hectare after cleaning, the minimum allowed distance between stems was 0.5 m, and as a target 10% of the remaining stems should be of deciduous species. To fulfil the "quality criteria" stems had to be undamaged, of preferred species, and within a preferred dbh range. The diameter ranges were selected to increase the mean diameter, but to reject stems with very large diameter. The "Reverse" simulation had the same settings as the "General" simulation but the "Reverse" simulation started in the opposite corner of the areas.

The following four simulations kept the settings from the "General" simulation except the altered value(s). The "Changed thresholds" simulation increased the importance of reaching the density target by altering the three thresholds. In the "4000-stems" simulation, the spacing parameter was decreased as the targeted number of stems per hectare was increased to 4 000. The "Increased minimum distance" simulation doubled the minimum allowed distance between stems. In the "30%-deciduous" simulation the targeted percentage of deciduous stems was increased.

To increase the available data for the six simulations, an old field inventory (OFI) by Gustavsson (1974) with eleven areas was included (*cf.* Fig. 1 in Paper III). These stands were described as representative Swedish cleaning stands but varied regarding *e.g.* density, species composition, and height. The utilised areas were 480 m^2 at each location. (Paper III). A thorough description of the OFI areas can be found in Gustavsson (1974).

In Paper IV results of the "General" simulation were used again and compared with the cleaners' results (presented in the section *Field "experiments" with cleaners*). An "Adjusted" simulation was also made where the preferred dbh range, targets for density, and targets for species mix were altered in accordance with the mean results of the cleaners. The minimum allowed distance between stems and the first two thresholds were set as in the "General" simulation. The last threshold was decreased (as in the "Changed thresholds" simulation). To fulfil the "quality criteria" coniferous stems were (as before) to be undamaged and within the preferred dbh range. However, both undamaged and damaged deciduous stems within the preferred dbh range were regarded as fulfilling all "quality criteria" in the "Adjusted" simulation. (Paper IV).

Field "experiments" with cleaners

Twelve professional forestry workers were engaged to "clean" the six field inventory areas (*cf.* Table 1). Forest companies were asked to appoint cleaners known for producing acceptable results, and the participating cleaners, all men, worked in south and central Sweden. They were instructed to select the remaining stems, as in an actual cleaning, considering the desired targets (similar to the General simulation):

- 2 500 stems per hectare
- 10% deciduous stems, "other deciduous" stems should be favoured to increase diversity
- At least 0.5 metres between each remaining stem
- Avoid selecting damaged stems

These experienced cleaners made their choices by indicating on a map the stems they decided to leave in the area. Each cleaner “cleaned” two areas and four cleaners “cleaned” each area. (Paper IV).

Field “experiments” with laymen

Four persons, with little or no forest knowledge, herein called laymen, were given a printed version of the DSS. The laymen functioned as substitutes for actual cleaning robots and were directed to follow the system’s recommendations, with the general settings for the DSS. They “cleaned” the SkutskärPine-area (*cf.* Table 1). The laymen were given the same damage definitions as the computer, but were allowed to decide for themselves which of the stems were damaged. They indicated on a map the stems they selected, with the aid of the DSS. They also indicated the reasons for their selections on this map. (Paper IV).

Laser scanning

Horizontal laser scanning was made in 2001, at two sites in a young forest stand near Bennikebol (Fig. 2). The stand had 7 000 stems per hectare, 50% coniferous and 50% deciduous, and the average height was four metres. Each scanning produced five different layers of data for each pixel: the mirror rotation angle, the laser-plane angle, distance, amplitude, and ambience. The raw data from the scanner was transformed into images, which were analysed to find more or less vertical lines, *i.e.* trees. Estimates of the height, diameter, and position of these “trees” were then made. (Paper V).

Statistics

Means and 95% confidence intervals (CI_{95}) were calculated for the results of the six simulations in Paper III regarding density, proportion of deciduous stems, and proportion of damaged stems. These values and the different simulations’ effects on the diameter were searched for significant differences ($p < 0.05$). When making pair wise comparisons, Tukey’s test was used to avoid mass significance. The 2-sided F-test was used to test for equal variance. When equal variance could be assumed pooled variances were used, and when two means of small samples with different variances were compared the statistics are referred to as the Behrens-Fisher problem (*cf.* Everitt 2002). (Paper III).

In Paper IV, treatment effects were analysed with analysis of variance. The experiment was analysed as a randomised block design, with cleaning method as treatment and area as block (*cf.* Eq. 8 in Paper IV). The three treatments, *i.e.* cleaning methods, were manual cleaning and the “General” and “Adjusted” simulations. In all analyses, there were five degrees of freedom for block, two for treatment, and 10 for error. Treatment means were compared using t-tests with Bonferroni corrections for multiple comparisons. Results were considered significant if $p < 0.05$. Means and CI_{95} were calculated for the cleaners (four in each area) and the laymen (four in one area) results regarding density, diameter, proportion of deciduous stems, and proportion of damaged stems (*cf.* Everitt 2002). (Paper IV).

Results

Papers I and V

A cleaning robot needs to find, select, and treat trees in the whole assigned area according to given instructions. The robot must be capable of moving safely within the forest environment, *i.e.* to navigate and localise itself automatically in a dynamic, non-deterministic and potentially hazardous environment. The vehicle's size and mass are of importance, *e.g.* it must be able to work between remaining stems. Furthermore, the robot must be safe for humans and animals, and it should not cause damage to remaining trees. To be cost effective it must be able to work independently night and day more or less throughout the year.

A robot must be able to adapt to various requests from different landowners regarding variables such as desired characteristics of main-stems, number of remaining stems, and percentage of deciduous trees. This makes identification and automatic selection of stems a critical phase in the development of an autonomous cleaning robot. Obstacle avoidance and target identification are identified as the most difficult problems. Machine vision, radar, and laser scanners, and combination of such sensors, are promising techniques for obstacle avoidance, tree identification, and tool control. It is possible to find trees in images produced with data from a laser scanner, and in Paper V the height and diameter of stems with a dbh < 0.05 m was possible to estimate. The above mentioned sensors may also be used to detect humans and animals, but inclinometers are needed to protect the vehicle from damage. Promising navigation and localisation techniques are combinations of GPS and Inertial Navigation Systems. Cost-effectiveness can possibly be reached by using solutions from the multimedia and automotive industries. There are a few relatively small machines currently operated by humans and autonomous systems used in other areas that have potential for further development, and there is also a cleaning tool that could be used. Software components needed for a cleaning robot includes a control system that is responsible for task planning, selection of main-stems, sensor handling, propulsion, and cutting operations and a target handling behaviour that deals with the main task for the vehicle, *i.e.* moving to a target-tree and cut it. Based on a hybrid of the reactive and hierarchical robot paradigms, an architecture for executing cleaning operations was proposed. The components in the architecture include the following functions: Mission planner, Sequencer, Cartographer, Resource manager, and Performance monitoring. To implement autonomous functions into a robot usable in forestry is however a very delicate task.

Paper II

The instructions given to cleaners working in an industrially owned forest are often rather stereotyped and NIPF owners usually request a "nice" stand. However, straight and healthy stems of the preferred species, with an advantageous size and position in comparison to surrounding stems, are favoured. Although, other stems might also be selected to meet the requested density target.

Skilful, experienced cleaners state that their selections are made automatically, whereas less experienced cleaners sometimes need to think for a brief moment. However, the time available to make selections is short, so they are constantly looking around, forming opinions about the stems as they walk through the stand. A cleaner should on average treat one hectare per day. The information accession range in young forests is restricted by obstructed views to approximately five metres.

Cleaners consider an even stand with many stems of the preferred species, *i.e.* many good options, easy to clean. Experienced cleaners think that less experienced cleaners sometimes detect damage too late and that they have a greater tendency than experienced cleaners to leave too many stems per hectare. Furthermore, inexperienced cleaners need more control and supervision. The contacts the entrepreneurs and cleaners have with the assigners are currently sparse. Previously, cleaners working for forest companies had training-days, in which a cleaner cleaned a designated area and an expert gave him feedback as he worked. Experienced cleaners do not perceive this shortage of information from the owner to be a problem. Nevertheless, cleaners think that they could make better selections if they had more time to perform their work. Time pressures have increased since the payment per hectare is currently about the same as it was ten years ago. The implicit "rules", *i.e.* their recurrent statements of preferred and unwanted characteristics, the cleaners use to complete their work differed somewhat from the explicit rules. There were apparent differences in the number of requested stems per hectare and the height allowed for untreated stems and there were also dissimilarities regarding the unwanted characteristics.

Paper III

The developed DSS selects main-stems by species, position (including distance and density parameters), diameter, and damage. Six simulations were run following the DSS, which showed that the results depend on the initial state of the stands, but generally the requested targets were met in an acceptable way. After the simulations the average density results deviated by -20% to +6% from the target values (Fig. 3, results of FI areas), the amount of deciduous stems shifted towards the target values, and the proportion of stems with defined damaged decreased from 14 - 90% in the initial stands to 4 - 13%. The mean diameter at breast height increased by 40 - 56% in the different simulations and the minimum allowed distance between stems was never violated.

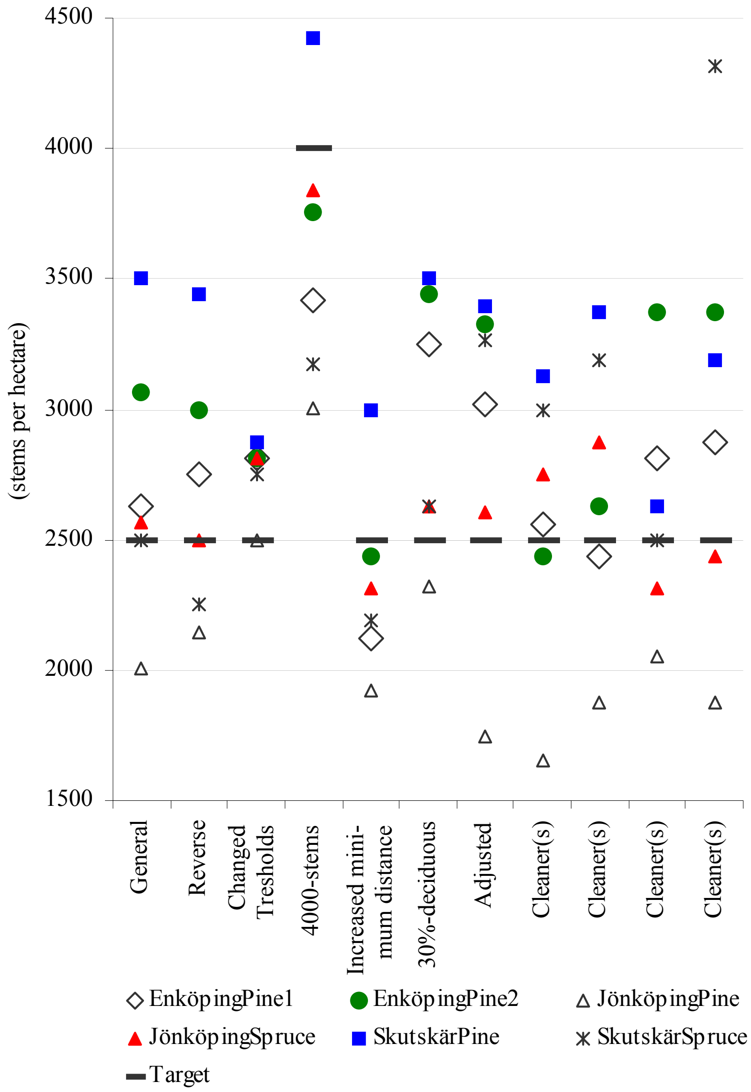

Figure 3. Density results in the FI areas after the simulations (Papers III and IV) and the results obtained by the 12 cleaners (Paper IV). *N.B.* four cleaners "cleaned" each area and one cleaner "cleaned" two areas, their personal reliability cannot be gauged from this figure.

Paper IV

The FI areas were used for a comparison of the results obtained by the cleaners and the results of the “General” and “Adjusted” simulations, which revealed that the stand density results were significantly affected by location (Fig. 3). The cleaners’ mean results for the density deviated by -25% to +30% from the instructions, the “General” simulations rendered similar variations (-20% to +40% in the different areas), and the “Adjusted” simulations deviated by -7% to +13% from their density targets, which were area-specific. The percentage of deciduous stems varied from 3.6% to 15.0% after the “General” simulation whereas the cleaners’ mean results were significantly higher, varying from 4.0% to 36.7%, and after the “Adjusted” simulation the proportion varied from 4.5% to 37.5%. So, the proportion of deciduous stems was significantly affected by both method and location. The proportion of damaged stems was also significantly affected by both method and location. On average more than 80% of the stems that were selected in one of the simulations were also selected by at least one cleaner, and about a third of the stems selected in the “General” and “Adjusted” simulations were also selected by all four cleaners. The results obtained by the laymen, who were instructed to follow the DSS with general settings, were close to the results of the “General” simulation.

Discussion

Research approach

The research method must be consistent with the aims of the research. The work of this thesis was explorative in its approach so the methods used were selected and adapted as it progressed.

The motive to perform reviews in the initial stage of this project (Papers I and II) was to assess the knowledge that already exists, although from a new perspective. Reviews are a cost-effective way to acquire knowledge, but can be incomplete when the research originally performed had another scope. For instance, research regarding automatic detection of trees has been made on larger trees (dbh > some 0.2 m) (*e.g.* Högström 1997, Clark *et al.* 2000, Forsman 2001, Tarp-Johansen 2001). Therefore, the potential ability of a laser sensor to find trees in young forest stands (dbh < 0.05 m) was investigated in an initial study (Paper V). The material in Paper V was limited, since the financial resources were restricted, but the study indicates that laser sensors may be used to find and measure small trees.

The review showed that cleaning manuals/instructions could not be used as a single source for automating the selection of main-stems as they are both too general and too detailed and mostly concern the end results. Still, cleanings are performed, so there seems to be tacit knowledge, *i.e.* persons involved in cleaning seem to have an implicit understanding of how to acquire relevant information, make selections and proceed within the stand. So, to gain an understanding of how practical cleanings are performed qualitative interviews were made. When humans are dealing with complex situations, they use only a few data to make decisions. Magnusson (1978) found that a typical doctor used from one to five out of ten available, considered important, values for making decisions about how much blood a patient should be given during a transfusion. Another test showed that a psychologists ability to predict a students result on a test rose when the available variables went from two to four, but with five or six variables the prediction ability was stabilised or even dropped (*ibid.*). The knowledge of a human expert is often heuristic in nature, based on useful ”rules of thumb” rather than absolute certainties (Cawsey 1997), see also the section *Automatic selective cleaning.* Heuristics can provide valuable shortcuts that can reduce both time and cost thus there is reason to explore the human heuristic search techniques as a source of ideas for developing “intelligent” computer-based systems (*cf.* Simon 1995, Giarratano & Riley 1998).

Semi-structured interviews were used as they can be modified over time, to focus attention on areas of particular importance or to adapt to changing circumstances or new understandings (Bliss & Martin 1989, Patton 1990). Qualitative methods are used for instance to study individual behaviour and motivations that are unknown a priori, which was the case here (*cf.* Bliss & Martin 1989, Strauss & Corbin 1990). There is no statistical test of significance to determine if qualitative results are valid (Eisner 1998). To overcome this limitation, cleaners with varying degrees of experience of forest work were interviewed (*cf.* Patton 1990).

To be able to automate the selection process a computer-based DSS was developed, which performs the same functions as a cleaner, but does not mimic humans. The reason for not including heuristic rules in the DSS was that the cleaners' implicit rules were unobtainable and perhaps wrong (discussed in section *Prospect of automatic selection of stems*). The advantage with a straightforward design, where the complexity of the task is reduced, is that once the attributes have been captured the decision process is deterministic and uncomplicated. A potential disadvantage is that the selections might be inferior.

However, the attributes used in the DSS were selected since cleaners and cleaning manuals/instructions mention them, as discussed in Paper II, and because it should be possible to detect them automatically, according to the results presented in Papers I and V. Although, attributes like species and damage require thorough and careful description in order to be determined automatically. The dbh ranges were used to increase the mean diameter and to reject stems with the largest diameter, *i.e.* to decrease the disparity in dbh and thus create a more uniform stand, which is a usual request according to Paper II. Another aspect of the attributes was that they had to be possible, at this point, for a human to measure. In the future, when information regarding the stems is provided through sensors, attributes like "amplitude" or IR-light *etc.* could be used. To have a practicable system, retrieved attributes and decision-making was limited to small-scale areas, as distant information usually is unobtainable when cleaning due to the restricted view (according to Paper II). The DSS was designed to have the ability to allow the selection of more stems than the average four, to compensate for sections not yet visited which could have a lack of desirable stems. However, when the settings in the DSS are adjusted to the initial stand and in accordance with the landowners requests this ability should be reduced since it can render overall results deviating from the target.

The field inventory was conducted to enable adjustments to be made to the DSS and thereafter to evaluate it (Papers III and IV). The DSS was developed to suit conventional Swedish cleanings stands, *i.e.* cleanings of stands at some three or four meters of height with a predominance of coniferous stems remaining after cleaning (*cf.* Brunberg 1990, Varmola & Salminen 2004, Ligné *et al.* 200X). A usual request at company owned forest is to have 2 500 stems per hectare after cleaning of which 10% should be deciduous (Paper II), and the FI areas were selected accordingly. It should be noted that dead trees were not measured as it was supposed that the DSS would be able to sense whether trees were living or dead. One of the reasons for making this field study was to acquire information about the stems' position with cm-precision. The stems' positions were needed to evaluate the DSS, *i.e.* to perform simulations. To enlarge the material for the simulations an old field inventory from the 1970s was included. This study had dm-precision regarding the stems' positions and another approach was used to class the trees in quality levels. However, including the OFI areas increased the available data and made it rather diverse (*cf.* Bergstrand *et al.* 1986). The stands are examples of Swedish forests, but it was not possible to determine their representativeness regarding the proportion of damaged trees and diameters, since the damage definitions were study-specific and no other larger studies considering the diameter were found. The density and proportion of deciduous stems seem to be acceptable according to Table 2. Furthermore, the FI areas were appointed by silvicultural managers as being typical cleaning stands of their organisations. The OFI areas were described as being representative cleaning stands in Sweden (*cf.* Gustavsson 1974), which seems correct according to Table 2, although it cannot be confirmed.

Table 2. Mean values for the density and proportion of deciduous stems in stands before cleaning as described in different studies

Variables	FI and OFI areas (17 areas)	Inventory of 1997 (457 stands)*	Vestlund 2001 (5 areas)	Swedish national inventories
Mean density (stems per hectare)	9 825 (dbh > 0.01 m)	8 000 (stems over 2 cm at cut-height)	12 640 (all stems in 2 areas and stems above breast height in 3 areas)	9-12 000[†] (all stems, inventory made in 1993-96)
Proportion of deciduous stems	46%	just above 50%	55%	62%[‡]
Mean height (m)	3.64 (OFI areas)		2.52	4[□] (newly cleaned areas)

* Pettersson & Bäcke 1998

[†] Values from the Swedish National Forest Inventory presented by Pettersson & Bäcke (1998)

[‡] Anon. 2002

[□] Nilsson & Gustafsson 1999

There are a large number of desirable and undesirable attributes of a tree (see Paper II) but the way individual selections of for example two “comparable” stems affect the stand development is not possible to exactly predict. Furthermore, the assigners’ actual requests are in some cases unsaid (see Paper II). This limits the possibility to make optimal decisions or an exact validation of the DSS. Thus, three other methods were used to evaluate the system. First, six simulations with different settings were run in the 17 areas, to evaluate how these settings influenced the results, and to assess the acceptability of the results (Paper III). To further evaluate the DSS a comparison was made with results of twelve cleaners (Paper IV). Kahle (1995), Zucchini & Gadow (1995), and Daume & Robertson (2000b) have used this method of evaluation in similar studies. A further intention of the comparison was to demonstrate differences between the cleaners, as this would imply that even if the DSS does not meet all of the targets it could be at least as good as a cleaner. Using a non-destructive method enables comparison of the cleaners’ results, but it is not certain that they would have made the same choices in an actual cleaning. The forest companies’ staff appointed cleaners that were said to perform at least acceptable results, but this of course cannot be verified. The results of the cleaners were also used to alter the settings and make an "Adjusted" simulation, in order to assess the possibility to adapt the DSS to their selections. Thirdly, laymen used the DSS for a cleaning to illustrate the systems potential utility for a robot, they functioned as substitutes for actual robots, and as a training-tool (Paper IV). However, it should be noted that this last method reflects not only the DSS's potential as a training-tool, but also my ability to rephrase the computer-rules into a "language" that people can understand. Still, the use of three different evaluation methods indicates the DSS's capability to reach acceptable results in a variety of situations. To further evaluate the DSS, and to refine the system if the assigners do not accept the system's selections, more simulations could be made according to alternative instructions given by the assigners. There is also an option of making comparisons with selections made by silivicultural researchers. The selections and results of the DSS could also be evaluated with a growth simulator, as the one presented by Fahlvik *et al.* (200X). However, that kind of evaluation is currently of less relevance, as the aim of this DSS was to be operational and to produce results accepted by assigners and comparable to cleaners.

Prospect of a cleaning robot

The importance of forestry is considerable for Sweden as a whole, but its importance for individual Swedes has changed. The first paragraph of Sweden's Forestry Act states that: "The forest is a National resource. It shall be managed in such a way as to provide a valuable yield and at the same time preserve biodiversity. Forest management shall also take into account other public interests" (Anon. 1995b). The perceived value of the forests has shifted from purely economical to become a recreational value for most people (*cf.* Hörnsten 2000). The multiple purposes of forests might be one reason that the production of timber is not usually regarded by ordinary people as the business activity it really is. However, continuous progress is needed in forestry to maintain its profitability and to meet the demands of the surrounding world.

Thus, is it likely that forestry, which has progressed from manual through motor-manual to mechanical operations, will be automated in the future? Will cleaning robots become practical realities? Perhaps, but as discussed in Paper I, there is still a long way to go.

1. An automated system must seem to render such advantages that it is interesting to develop.
2. The robot must be able to operate in forest environment, in real-time.
3. It must be possible to integrate the robot in a silvicultural system at large, *i.e.* it must function and operate in organisations of people and other machinery.
4. The whole work operation for cleaning must be described from a robot's perspective.

Since systems for cleaning (manual, motor-manual, mechanical and chemical) already are available, it is necessary for a new system to appear as more attractive by *e.g.* decreasing the workload, improving the quality, and/or decreasing the costs (Nåbo 1992). Changes in regulations may also force a system change, as can be seen in Canada, where the use of herbicides is already prohibited in Quebec and being debated in other areas (*cf.* Ryans & St-Amour 1996, Pitt *et al.* 2000, Anon. 2004b).

The most challenging problems in developing a robot usable for cleanings are probably obstacle avoidance and target identification in the forest environment. Combinations of machine vision, radar, and laser scanners appear to be promising solutions. Necessary sensors, algorithms, and methods to develop and demonstrate operationally viable outdoor autonomous vehicles already seem to exist (*cf.* Durrant-Whyte 2001). However, it is not possible to state at this early stage of the development of robots whether they will be able to deliver reductions in costs or better work environment for the personnel. A cleaning robot would be quite expensive considering all its technical equipment. The economy of it is based on the prospective use of an inexpensive base-machine and off-the-shelf equipment/solutions from other industries/areas of research. Design issues regarding *e.g.* the robots propulsion, size, and tools should be easier to solve, as there already exists fully operational forest machinery. For example, in 1995, the forest machine company Timberjack presented a walking harvester (*cf.* Anon. 1997).

In order to reduce labour costs, *i.e.* costs of operators, the robot should solve common problems automatically, although it must be able to call for assistance when it encounters unusual difficulties. This indicates that its productivity per hour could be lower than that of conventional methods. In a normal week a cleaner works 40 h. If the robot could work unattended throughout the week, both night and day, it would have 168 hours available, *i.e.* it could be four times slower and still compete with a cleaner if its cost per hectare was equal. In comparison with traditional forest machinery, which is used up to 3000 h per year, a robot working continuously has 8760 h available per year. However, transportation between sites, situations with faults or alarms, and maintenance would decrease the productive time and the cost per hour might be higher for the robot.

A robot would turn the personnel into operators, releasing them from heavy workloads, but might increase their mental burden (see also the section *Changing the system*). However, the current cleaning situation is not sustainable in the long-term as it is not possible to expect that there will always be persons available to work for a low remuneration. Thus, there is or at least will be a need for change. Both time and effort is needed in order to develop a cleaning robot, and forest machine manufacturers differ in their opinion regarding whether or not robots will become reality in the future (*cf.* Jansson 2001, Thorner 2004). To promote automation in the forestry sector an expressed desire from the forest companies is essential. NIPF owners might have other interests in their forest than strict economical (Hugosson & Ingemarsson 2004) and, furthermore, they probably do not have the financial strength to take up the cudgels for automation of forestry operations. There is yet a long way to go before fully operational robots for forestry are available. To implement autonomous functions into a robot used in complex environments, like the forest, is difficult since such a robot not only have to build maps and find its way through the unknown forest but also perform assignments, *e.g.* cleaning, when it has reached its destination (*cf.* Uhlin & Johansson 1996). The answer to this general problem in robotics is hybrid systems that combine hierarchical and reactive components (*cf.* Blackmore *et al.* 2002) and in Paper I a proposed system design for a cleaning robot with hybrid and reactive behaviours is presented. Murphy (2000) states that in the hybrid deliberative/reactive paradigm the robot first plans (deliberates) how to best compose a task into subtasks (also called mission planning), and then what are the suitable behaviours to accomplish each subtask, *etc*. Then the behaviours start executing as per the reactive paradigm (*ibid.*). In the reactive paradigm all actions are accomplished through behaviours. Behaviours are a direct mapping from sensory inputs to motor outputs that are used to achieve a task (*cf.* Brooks 1986, Murphy 2000). Thus, it seems more likely that an autonomous shuttle system, operating in pre-planned paths, replacing the forwarder will appear first (Thorner 2004).

Changing the system

Current system

The current cleaning system often involves more than one person, especially when done professionally. NIPF owners usually do the cleaning themselves (Lidestav & Nordfjell 2002), but otherwise cleaning entrepreneurs or cleaners do it. Their equipment consists of: cleaning-saw, blades, files for the blades, fuel, and protective clothing (Fig. 4). Public and forest roads are used for transportation, and cars or vans are needed to transport the personnel and their equipment. Such transports should be quite easy to organise, but the transportation of rest-huts needs some planning.

Figure 4. A person equipped for motor-manual cleaning.

A cleaning operation typically consists of the following tasks:

- Planning in the office
- Planning in the forest (*e.g.* marking borders with paper-strips)
- Actual cleaning
- Maintenance of the saw
- Follow-up work

The cleaning system relies on back-up systems including mechanical service and the provision of spare parts, road maintenance and construction, as well as planning and administration.

Automatic system

The way cleaning operations are organised might not be changed, but the assignments will change with an automated system. The cleaners will become operators and their education will need to be modified to handle the machine. The operators will be in charge of the (probably quite expensive) robot(s) and must be capable of controlling the robot as well as perform daily-maintenance of it. The operators will also plan and follow-up the work. If one person does not possess all the required knowledge, a team of persons with different skills could work together, and perhaps learn from each other. Team-work is frequently used in changing environments (Scott 2003). However, team-building is a delicate task, and needs thorough analysis. Even when the 2-man chain saws were introduced in Sweden Zimmermann (1948) stated the importance of selecting operators with great care. Similarly, when mechanical cleaning was introduced at the forest company Stora, the importance of selecting team-members was stressed (Tosterud & Bergqvist 1990).

Current cleanings involve little pre-planning (Vestlund 2001b). If the work was done with a robot more planning might be needed, and it would certainly have to be computerised. For example, the area selected for treatment could be marked out from the surroundings and the route for the machine to take could be planned in advance on digitised maps. There might also be areas that are not suitable for a cleaning robot, which would have to be treated conventionally with cleaning saws. Map information used by forest companies is already usually digitised and could probably be transformed for use in an autonomous process. However, cleaning with robots might require more rigorous planning, *e.g.* to make the correct settings in order to have acceptable and requested results. The robot would produce results according to the given instruction (see also the section *Automatic selections with the DSS*). If the robot should be unable to follow the given instructions it should stop and call for assistance.

Robots would probably be transported on small trucks and their transport might need organisation. Introducing a robot would make maintenance and service work more complex than sharpening the saw-blade and repairing or buying a new cleaning-saw. Furthermore, some of the service would have to be done by trained personnel and the amount of spare-parts required would also increase.

Introducing robots would not only affect the system itself and the back-up systems but also, perhaps, the associated systems, *e.g.* reforestation, thinning and final felling, and vice versa. For example, data regarding the main-stems selected in the cleanings could be used to locate and select stems later in the rotation period for thinnings. Furthermore, if reforestation was done with a planting-machine it might be possible to collect data concerning where seedlings have been planted and the location of scarification rows. Such information could then be utilised in the search for main-stems. Data revealing where a seedling has been planted does not assure that a main-stem can be found there, but the probability is higher. Data on scarification rows may be of lower quality, since scarified areas do not need to bear the best or at all any stems.

Furthermore, introducing a robot also raises psychological issues. People might feel uncomfortable with the thought of a machine working autonomously in their neighbourhood. It is also possible that forest workers will object to this development if they believe that the robot will reduce their employment prospects. On the other hand there are concerns that there will be a shortage of skilled machine operators in the future (Jansson 2001).

Prospect of automatic selection of stems

Basis of stem-selection

The first issue to consider in order to automate stem selections is the ability of robots to find and locate stems in young forests, and Paper V indicates that this is possible. When the stems are found decisions must be made about which stems should remain and which should be cut. There are a large variety of cleaning performances, *e.g.* point cleaning, cleaning in stands with shelters (*cf.* Anon 1999a, Normark & Bergqvist 2000, Vestlund 2001a). Thus, current requests for cleaning must be transformed and represented in such a way that a robot can adapt to various instructions from different landowners and accomplish satisfactory results in varying forest types.

Decisions can only be made in accordance with available instructions and information. There are at least four difficulties when making a decision to select a stem as a main-stem.

- Time limitations
- The small-scale of the area that can be considered
- Uncertainty
- Limited feedback

There are considerable time-pressures in cleaning; if one hectare with 5 000 stems is treated during one day there is less than 6 s for every stem. Thus, there can be no detailed investigations regarding which stem to leave or remove.

Practical selection of main-stems in cleaning must also rely on information concerning a small area because the view is obstructed. The decision situation is uncertain and complex (as stated in *Automatic selective cleaning*), but research has shown, for example, that there seems to be quite small opportunities to reduce branch dimensions relative to stem size through competition for individual stems in pine stands (Mäkinen 1996). So, if stems with thin branches are preferred, the stems with relatively thicker branches should be removed. There are also other explicit and implicit "rules" that must be taken into consideration during the selection process. To mention one example: A cleaner described (in Paper II) a decision situation in which he had to chose between leaving rather small spruces or instead leaving larger birches of inferior quality, as difficult.

The human way to solve complex problems cannot be described objectively since the persons involved are not fully aware of how they make their choices. The human decision-making process depends upon how information is chosen and utilised. In such a process the conceptions of reality and the personal limitations of the persons involved play a decisive role (Magnusson 1978). Interviewed cleaners express clear preferences concerning the characteristics of preferable main-stems, but they cannot explain their implicit "rules" they use to select stems. However, there is little reason for revealing these "rules of thumb", since the cleaners get limited feedback. This makes the quality of their rules questionable, because feedback is essential for persons to learn how their rules work (*cf.* Magnusson 1978). Without feedback the rules also become individual; every cleaner makes his own rules. Some cleaners have been working with cleaning for many years and probably acquired their rules in the past, when they had feedback. However, the requested performance parameters might have changed over the years. The cleaners might only learn what their colleagues think they "know".

Furthermore, the correlation between the instructions and the results seems poor in some cases. Pettersson & Bäcke (1998) state that generally cleaning sites had 4 000 stems per hectare remaining after cleaning, although the requested target is usually 2 500 according to Paper II. However, results of the experienced cleaners in Paper IV were quite close to the density target on average, but five of them were always above the target, and all twelve were above the targeted proportion of deciduous stems in at least one of the areas they cleaned. These findings are consistent with reports by Daume *et al.* (1997), who found that thinning results depend on the thinning personnel, and Kahn (1995), who found that tree selection for cutting during thinning was based partly on subjective criteria and partly on indistinct instructions. Therefore, applied cleaning is and must be done with a satisfactory approach and the amount of information and knowledge that is needed to produce acceptable results might not be immense.

Automatic selections with the DSS

The aim of the presented DSS is first and foremost to have an operational automatic system accomplishing results comparable to cleaners. The simulations were made with settings that aim to reduce the density in the treated area, but also to decrease the final number of damaged stems. There might also be interest in adjusting the species composition and evening the stand. The DSS uses four attributes for differentiating the stems (species, position, diameter, and damage) and it does not include the type of rules incorporated in an expert or KB system, *i.e.* it does not contain AI at this point. Complex situations are said to require intelligent decision support, *i.e.* AI software (*cf.* Simon 1995). However, to reduce the level of autonomy needed for executing complex tasks in a complex environment one can reduce the complexity of the task and/or the environment (Uhlin & Johansson 1996). Here, the complexity of the selection process has been reduced, but the settings in the proposed DSS can currently be shifted to adapt to various requests and the DSS seems to generate acceptable results. Although, in the future, when attributes like species and damage are to be automatically sensed, AI software for pattern recognition is likely to be needed.

There were some variations in the simulations' results, but on average acceptable cleaning results were generated in a variety of forest types (FI and OFI areas) according to the general cleaning follow-up (Paper III). The results were also acceptable in comparison with the cleaners' results (FI areas, Paper IV), although the cleaners selected more deciduous and damaged stems. With the "Adjusted" simulation the DSS was able to produce results comparable to the cleaners' choices.

The initial state of the stand affects the possibility to meet the targets, especially the requested species mix, as stems must be selected throughout the whole area and some parts of the stand may lack the desired species. The amount of stems fulfilling the "quality criteria" (defined in section *Simulations*) was a major factor affecting the variations in stand density after the different simulations. The underlying idea was that the number of undamaged stems would affect the density results of the cleaners. This idea was tested in Paper IV and seemed to be valid for all of the areas except the SkutskärSpruce-area. However, the largest differences between cleaners were found here, *i.e.* the inter-personal reliability was low, suggesting that the concept should not be dismissed.

The simulated cleanings substantially decreased the percentage of stems defined as damaged. The difference between the cleaners' and the "General" simulation results regarding the proportion of damaged stems is due to underestimation of the cleaners' tolerance for selecting damaged deciduous stems. Furthermore, the cleaners selected twice the instructed percentage of deciduous stems, on average. Damaged stems should perhaps be tolerated in some cases, *e.g.* stems browsed by moose could remain in the interest of wildlife, if they are not competing with main-stems (*cf.* Anon. 1999a). When more stems were to be left in the "4000-stems" simulation or the target proportion of deciduous stems was increased in the "30%-deciduous" simulation, the amount of stems with damage increased as inferior stems had to be selected when no better alternatives existed.

On average, the mean dbh increased from the initial values (FI and OFI areas, Paper III), and was comparable to the cleaners' mean results (FI areas, Paper IV). However, all simulations rendered a lower mean dbh than the mean results of the cleaners in JönköpingSpruce and slightly lower mean dbh values for coniferous stems in SkutskärSpruce. The simulations rendered higher mean dbh for deciduous stems than the cleaners' results in EnköpingPine1 and SkutskärSpruce, as too few deciduous stems fulfilled the "quality criteria". This caused the selection of any available undamaged stems, or when such stems were not present damaged stems were selected, and in these cases the stems with larger diameter were preferred.

The precision at the single-tree level for the DSS compared with the cleaners seems promising, as more than 80% of the stems selected in the "General" and "Adjusted" simulations were selected by at least one cleaner. When comparing individual cleaner's results with the "General" and "Adjusted" simulations, on average, 63% and 60% (respectively) of the stems selected were also selected by a cleaner. Similar studies in thinning by Kahle (1995) and Daume & Robertson (2000b) have reported agreement levels of 56% and 52%, respectively. However, the amount of remaining stems with "undefined damage" was higher for the simulations, suggesting that trees with very few living needles/leaves should be defined as damaged. The variations in the cleaners' results also seemed to be within the normal range (*cf.* Kahle 1995, Zucchini & Gadow 1995, Füldner *et al.* 1996).

A problem that could arise with automatic stem selection is that the results might be too uniform, as the personal variations are removed, but as the forest varied the results of the DSS also differed. However, different stand types should have customised cleaning instructions and the instructions should also vary according to the objectives of the forest, *i.e.* targets for stand density, diameter, and the species mix should be selected in accordance with the initial state of the stand and the assigners' requests. This also includes that different targets may be needed in different parts of a stand. If the stand variations could be considered in the planning stages, the ability to meet the targets would rise.

With varying target settings in the DSS the prospect to reach results comparable to those of humans would also rise. Nevertheless, it is not necessarily essential to conform fully to the cleaners' results, since it is questionable whether all of the cleaners' choices were desirable, even if they were acceptable. Some cleaners were clearly above the stand density recommended by cleaning manuals and the proportion of deciduous stems did sometimes seem high. However, forest owners might have other objectives than those obtained with a standard instruction and could consequently find these results adequate. It is important to remember that a DSS follows given instructions rigorously, whereas cleaners sometimes deviates from them.

The potential for using the DSS as a tutoring instrument seems promising. The laymen were able to use the DSS, and although they deviated from the DSS-recommendations in some cases their results were close to the results of the "General" simulation. A DSS provides immediate and objective directives about how to proceed, which the cleaners' request. So if this DSS provides correct recommendations and can provide better decisions it can be expected to lead to better outcomes (*cf.* Druzdzel & Flynn 2000). If the selection process could be improved and render "better" results there is a possibility that the landowners would tolerate a higher cleaning cost, or at least accept the costs as of today. The DSS could also be used to communicate detailed requests of the assigners to cleaners. Such a system could also be useful when the cleaner finds the selections difficult to make, and may help inexperienced cleaners to make better (*i.e.* closer to requested) selections and perhaps learn faster. The lack of feedback can clearly be a problem of the new generation of cleaners. A DSS for humans could use other attributes, than those selected here, as there is no restriction to use attributes possible to detect automatically, see also *Future research*.

Suggested improvements for the DSS

The DSS sometimes allow selection of more than four stems in an area, settled by the settings in one threshold (T3, see Paper III). Perhaps there should be a limit to how many selected stems a section should have. This problem is, however, connected to the settings in the DSS. When the settings are adjusted to the stand, the problem of having many stems in one section, in order to meet the overall density target, would be reduced.

In this DSS a stem is either selected as a main-stem or rejected and there is no differentiation between the stems in the two groups. Currently a stem is regarded as damaged if it has one or more of the defined types of damage. No grading of the damage types was made since the relative seriousness of different types of damage cannot be correctly assessed. There will always be some unidentified types of damage in a DSS because they are undefined (rare). Damage may also be missed because of view restrictions. However, more types of damage should perhaps be added to the DSS as stems with very few living needles/leafs are currently accepted as undamaged, and grading of damage of each damage type could be an alternative approach when damaged stems must be selected.

Since the selected FI areas either were dominated by pine or spruce (regarding the coniferous stems) these species were not separated in the current DSS. This condition should probably be added and it could be handled as the birch is handled in the presented DSS. Furthermore, this DSS does not deal with “fruit-bearing” species *e.g.* mountain ash (Sorbus aucuparia L.), bird-cherry (Prunus padus L.), and juniper. These species should always be retained (Anon. 1999a) so this is a condition that should be added to the system. Furthermore, branch diameter and height are attributes that should perhaps be added if/when proper estimations with automatic techniques of these attributes can be made (*cf.* Clark *et al.* 2000, Paper V).

Alternative approaches for future cleanings

The costs of cleaning are considered high, and NIPF owners do not always see cleaning as an investment (Karlsson 200X). Furthermore, some of the cleaning entrepreneurs and cleaners feel that their profitability has been reduced (*cf.* Vestlund 2001a). A cleaning robot could rationalise the work but there are also other approaches.

An alternative to motor-manual selective cleaning is mechanical cleaning, but its cost-effectiveness has hitherto been uncertain (Ligné 2004). Another drawback with mechanical selective cleaning is the stress put on the operator when manoeuvring the crane to cut discharged trees without damaging remaining trees (Gellerstedt 1997). Cleaning with a geometric pattern would release the operator from this stress. Pettersson (2001) argues that generally every other stem in young Scots pine stands have some kind of damage, usually a spike branch or crook, and these damaged trees are more or less clustered in the stand. So, these findings suggest that selectivity has little influence on the amount of damaged trees. However, 10 years after cleaning Scots pine stands with initial densities of some 10 400 stems per hectare on average the volume of larger stems (dbh > 4.5 cm) was 93% after selective cleaning, 84% after geometrical cleaning, and 75% without cleaning (Pettersson 1986, Tham 1987). Brissette *et al.* (1999) have analysed the basal area of crop trees[‡] 18 years after cleaning of coniferous stands with an average initial density of 42 700 stems per hectare in north-east Maine, USA. They found that the crop trees in areas that were cleaned selectively or with a combination of strip-cleaning and selective cleaning had basal areas of 20.5 and 18.3 m^2 per hectare, respectively. This was significantly higher than the strip-cleaned areas that had 8.7 m^2 per hectare, which in turn was significantly higher than the untreated area, where the crop trees had produced only 5.2 m^2 per hectare (*ibid.*).

These findings indicate that a geometrical cleaning is better than none at all, and it should be easier to develop a robot for geometrical cleaning since the delicate selection process is removed. However, the coniferous stems in the FI areas were not heavily damaged (11 - 30%), and the damaged trees were not clustered. In addition, selection of individual stems would allow the stand characteristics to be adjusted. Non-selective cleaning reduces the opportunity to affect the species composition, which could be of interest even if it is not possible to decrease the proportion of damaged stems in the stands, since certain species are more valuable than others. Combining strip cleaning with selective cleaning in the residual strips seems to generate comparable results and to be cheaper than traditional motor-manual selective cleaning (*cf.* Brissette *et al.* 1999, Bergkvist *et al.* 2004).

Another idea that has been suggested to facilitate mechanised cleaning is to use alternative planting methods. If the plantations were made in rectangular patterns with prepared “paths” for the machines instead of the usual squared pattern, the cleanings would be easier to perform (Fryk 1985, Glöde & Bergkvist 2003). However, rectangular patterns might cause unfavourable effects like oval stems and trees with thick branches (*cf.* Tham 1987, Bergkvist *et al.* 2004).

Utilising small trees that are cut in cleanings for fuel is an idea that has received some interest in Sweden in the last 10 years (Brunberg *et al.* 1998). This is expected to increase the income from forestry and at the same time provide a source of energy with no net carbon-dioxide contributions (Björheden *et al.* 2003). With gross receipts from the cleanings the sensitivity for the operation costs

[‡] 1682 trees per hectare were selected as crop trees in the study.

decreases. However, it has been argued that this management make the forest owners postpone their cleanings in order to increase the harvest of bio-energy, which increases the risk of damage to the stand (Johansson 2000). Forest fuel removal also cause a decrease in available nutrients, however, this can be compensated with *e.g.* recycling of wood ash (Anon. 2001b).

Future research

Issues that must be solved before a cleaning robot can become a practical reality include the development of safe techniques for obstacle detection, localisation and propulsion. Safety is often believed to be the hardest problem in developing automated unmanned vehicles (Reid 1998, Stentz 2001). The problems to be addressed involve avoidance of human injury and damage to vehicles and environment. The most challenging problems in developing a robot usable for cleanings are probably obstacle avoidance and target identification in the forest environment. For example, more laser measurements are necessary in order to discover the types of forests in which this technique could be used for target identification. Other types of sensors should also be tested, *e.g.* millimetre-wave radars, which are more robust to fog and rain than laser beam sensors. Furthermore, the method used in Paper V for making estimations of the trees is neither fully accurate nor fully automatic and this is another area of research that deserves attention before cleanings can be automated. For instance, some kind of a probability test could be included in the method to determine if the dbh is reasonable in relation to the tree's height. Hence, further research on image analysis is needed to successfully find and measure small trees (dbh < 0.2 m). Moreover, producing a machine that autonomously perform practical stem selections and cut rejected stems requires much more research and development (regarding *e.g.* positioning, cutting, felling). As mentioned above, implementing autonomous functions into robots are complicated and the forestry research community will have to cooperate with other scientists to create capabilities for an inexpensive autonomous base-machine, which could be used in cleanings, to be built. Once a robot for out-door environment is available it should be easier to equip it with tools for forestry operations such as cleaning.

Future silviculture might shift radically in a way that is not yet known. Rydberg (1992) discusses cleaning in recreational forests and suggests that the intensity should be varied to favour various interests. There are also ideas that cleanings should be done in such a way as to increase the irregularities in a stand (Hagner 1997). Whether or not the presented DSS can adapt to all the possible requests remains to be seen, but the DSS can be further developed if needed. To further evaluate the DSS, tests in computer-generated forests could be made. Such tests could reveal its sensitivity to the precision of the different attributes. In the future, when the attributes are measured with sensors, it is likely that the precision will be lower than in the presented inventory and thus these kinds of tests could be of interest. Each attribute could be varied individually in the "cyber forests" to obtain more detailed indications of conditions in which the DSS might render unacceptable results. Some initial attempts to create simulated forests were made in cooperation with "Högskolan i Gävle" during this PhD-project (*cf.* Lehnbom & Larsson 2003).

The presented DSS should be possible to use for semi-automation, *e.g.* when a person operates a machine but the actual cleaning and selections being generally done autonomously. Such a semi-automated system could also lead to a fully autonomous system since this approach would allow the system to learn from choices that the human operator makes, so the degree of autonomy could be successively increased (Uhlin & Johansson 1996). There is also a possibility that the presented findings will be of use in other forest operations, like thinning, harvesting or forwarding. The possibility of modifying the DSS for use in thinnings should be investigated, since it should be easier to make the thinning operation semi-autonomous as human operated machines currently are used to perform this operation.

Acceptable or satisfactory cleaning results can be reached through a variety of cleaning performances. However, it is important, for silvicultural practices in general to know the probability that a given instruction will generate a specific result. Current instructions and manuals seem to be too theoretical and too focused on the end results, and there appears to be a need to develop better cleaning instructions as the cleaners are sometimes uncertain of what the assigners actually request. Füldner *et al.* (1996) found that the motive for selecting a particular tree in thinning sometimes is difficult to predict, although foresters are given the same instructions. This illustrates the difficulty current instructions have, for cleaning as well as thinning, to render consistent decisions. However, different selections are not necessarily a proof of poor performance since most cleaning results are acceptable, but suggest that there are alternative ways to select stems. Further analysis of the given instructions and preferred results, together with better follow-ups, could, however, be used to improve motor-manual cleaning and to refine the presented DSS. With more research in this area it should be possible to modify this DSS into an expert or KB system, *i.e.* include "expert" rules in a knowledge base and an inference engine that interprets and evaluates facts, instructions and data in the knowledge base. Perhaps the above mentioned growth simulator by Fahlvik *et al.* (200X) could be useful for this kind of development.

Conclusions

This thesis identifies specific features of the forest environment and forest operations that must be considered in the development of autonomous cleaning robots. A large number of problems must be solved if robots are to be used in the forest. Any such robot must have the ability to operate independently and unattended for several hours. Apart from the central issue of finding and selecting trees, all cleaning tasks must be described from a robot's perspective. These tasks include moving around in the dynamic and non-deterministic environment of a forest, cutting and felling trees, and treating the whole assigned area without damaging remaining trees. Obstacle avoidance and target identification are identified as the most difficult problems. The desired results of cleaning must be represented in such a way that a computer can accomplish satisfactory results in varying forest types and adapt to various requests from different landowners. It must also be possible to integrate the robot in a silvicultural system at large, *i.e.* it must function and operate in organisations of people and other machinery. If robots usable for forestry are to become a practical reality the anticipated advantages must be so high that the investment required in research and development seems worthwhile.

The selection of main-stems is important in selective cleaning, but must be quick to be cost-effective. Furthermore, practical selection of main-stems in cleaning operations must rely on data concerning small areas, since information beyond a certain distance is unobtainable. The forest environment is complex and consequently cleaning is and must be done with a satisfying approach. It was not possible to retrieve the cleaners "rules" so the developed DSS is based on the cleaners' recurrent statements of preferred attributes in combination with written instructions.

The state of the initial stand will influence the results of the cleaning operation, *i.e.* different stand types should have separate cleaning instructions. However, the DSS produced acceptable results in a variety of forests indicating that it is useful. The comparison between the cleaners' and the DSS's selections showed that the cleaners' results were comparable to those of the simulations with general settings in the DSS. However, the proportions of deciduous stems and damaged stems were higher for the cleaners. In the "Adjusted" simulation, when the settings were altered in line with the results' of the cleaners, it was possible to generate results comparable to those of the cleaners. Using the DSS in automatic, or semi-automatic, cleaning operations should be possible, but only if and when the selected attributes can be automatically perceived. Using the DSS as a training-tool for inexperienced cleaners is an interesting option as of today, and with an improved interface the prospect of following the recommendations of the DSS would rise. With a DSS the cleaners would get more immediate directives about how to proceed, which they request. A DSS for humans could use other attributes, than those selected here, as in that case there is no restriction to use attributes that should be possible to detect automatically.

References

Ahlén, I. (Ed.) 1971. *Fenoxisyror: granskning av aktuell information -rapport från en expertgrupp* [Phenoxyacetic acids: examination of current information - report from an expert group]. Giftnämnden, Allmänna förlaget, Stockholm, Sweden. 136 p. (In Swedish).

Allen, G. & Gould, E. 1986. Complexity, Wickedness and Public Forests. *Journal of Forestry, 84(4)*: 20-23. ISSN: 0022-1201.

Andersson, S.O. 1985. Röjning och sågtimmerkvalitet [Cleaning and timber quality]. In: Kvalitet - behöver vi det? Skogshögskolans höstkonferens, 4-5 december 1984, Uppsala. *Skogsfakta Konferens, nr 6, Skogsvetenskapliga fakulteten, Swedish University of Agricultural Sciences*, Uppsala, Sweden. p. 33-38. (In Swedish). ISSN: 0282-7360.

Andersson, S. 1986. Visionära möjligheter och verkliga problem inom skogstekniken [Visionary possibilities and real problems within forest operations]. *Sveriges skogsvårdsförbunds tidskrift 84(1)*: 17-25. (In Swedish). ISSN: 0371-2907.

Anon. 1978. *Skogsstatistisk årsbok 1976* (Statistical yearbook of forestry 1976). Skogsstyrelsen, Jönköping, Sweden. 311 p. (In Swedish with English summary). ISBN: 91-38-04028-X.

Anon. 1979. *Skogsstatistisk årsbok 1977* (Statistical yearbook of forestry 1977). Skogsstyrelsen, Jönköping, Sweden. 275 p. (In Swedish with English summary). ISBN: 91-38-04805-1.

Anon. 1985. *Skogsstatistisk årsbok 1985* (Statistical yearbook of forestry 1985). Skogsstyrelsen, Jönköping, Sweden. 248 p. (In Swedish with English summary). ISBN: 91-85748-48-X.

Anon. 1987. *Skogsstatistisk årsbok 1987* (Statistical yearbook of forestry 1987). Skogsstyrelsen, Jönköping, Sweden. 283 p. (In Swedish with English summary). ISBN: 91-85748-63-3.

Anon. 1992. *Skogsstatistisk årsbok 1992* (Statistical yearbook of forestry 1992). Skogsstyrelsen, Jönköping, Sweden. p. 238. (In Swedish with English summary). ISBN: 91-85748-95-1.

Anon. 1995a. *Collins English Dictionary*. 3rd Ed. HarperCollins Publishers, Glasgow, UK. p. 103. ISBN: 0 00 470678-1.

Anon. 1995b. *The Swedish forestry act*. National Board of Forestry, Jönköping, Sweden. 11p.

Anon. 1997. Succé för Elmia Wood [Elmia Wood, a success]. *Bioenergi, nr 4*. p. 12. (In Swedish). ISSN: 1403-6746.

Anon. 1998. *Skogsstatistisk årsbok 1998* (Statistical yearbook of forestry 1998). Skogsstyrelsen, Jönköping, Sweden. p. 239. (In Swedish with English summary). ISBN: 91-88462-34-X.

Anon. 1999a. *Röjning* [Cleaning]. StoraEnso Skog, Falun, Sweden. p. 10-11, 24. (In Swedish).

Anon. 1999b. *Developing stand density management regimes.* Ministry of Forests, Victoria, British Columbia, Canada. p. 11-16. ISBN: 0-7726-3746-6.

Anon. 1999c. *Skogsstatistisk årsbok 1999* (Statistical yearbook of forestry 1999). Skogsstyrelsen, Jönköping, Sweden. p. 240. (In Swedish with English summary). ISBN: 91-88462-40-4.

Anon. 2001a. *Annual Report.* Forest Engineering Research Institute of Canada. Pointe-Claire, Quebec, Canada. p. 8.

Anon. 2001b. Rekommendationer vid uttag av skogsbränsle och kompensationsgödsling [Recommendations for forest fuel removal and compansation fertilization]. *Meddelanden Nr 2, Skogsstyrelsen,* Jönköping, Sweden. 16 p. (In Swedish). ISSN: 1100-0295. Available on the net at: www.svo.se/forlag/meddelande/1518.pdf (accessed 27-July-2005).

Anon. 2002. Skogsdata - aktuella uppgifter om de svenska skogarna från riksskogstaxeringen, Tema: Ungskogar [Forestry data - current information of the

Swedish forests from the Swedish National Forest Inventory, Focus: Young forests]. *Department of Forest Resource, Management and Geomatics, Swedish University of Agricultural Sciences*, Umeå, Sweden. p. 5-14. (In Swedish). ISSN: 0280-0543.

Anon. 2004a. *Skogsstatistisk årsbok 2004* (Statistical yearbook of forestry 2004). Skogsstyrelsen, Jönköping, Sweden. p. 110-112, 121, 123, 223, 235. (In Swedish with English summary). ISBN: 91-88462-61-7.

Anon. 2004b. *Compendium of Canadian Forestry Statistics. Canadian Council of Forest Ministers*, Ottawa, Canada. Published on the net: nfdp.ccfm.org (accessed: 2005-02-21). ISSN: 1188-5815.

Aussenac, G. & Granier, A. 1988. Effects of thinning on water-stress and growth in Douglas-fir. *Canadian Journal of Forest Research 18(1)*: 100-105.

Berg, H., Bäckström, P.O., Gustavsson, R. & Hägglund, B. 1973. Några system för ungskogsröjning - en analys [Analysis of some systems for cleaning of young forest stands]. *Redogörelse Nr 5, Forskningsstiftelsen Skogsarbeten*, Stockholm, Sweden. p. 12. (In Swedish).

Bergkvist, I., Johansson, F. & Glöde, D. 2004. Tredje generationens röjningsteknik, maskinell röjning i stråk kombinerad med motormanuell mellanzonsröjning [Third generation cleaning technique, mechanical strip cleaning combined with motor manual cleaning in residual strips]. *Arbetsrapport, nr. 566. SkogForsk*, Uppsala, Sweden. 25 p. (In Swedish). ISSN: 1404-305X.

Bergkvist, I. & Nordén, B. 2004. Stråkröjning billigare och effektivare än selektiv röjning (Corridor cleaning: cost effective and more efficient than selective cleaning). *Resultat nr. 20, SkogForsk*, Uppsala, Sweden. 4 p. (In Swedish with English summary). ISSN: 1103-4173.

Bergstrand, K.G., Lindman, J. & Petré, E. 1986. Underlag för prestationsmål för motormanuell röjning (Instruments for use in setting productivity targets for motor-manual cleaning). *Redogörelse nr 7, Forskningsstiftelsen Skogsarbeten*, Spånga, Sweden. p. 7, 15. (In Swedish with English summary). ISSN: 0346-6671.

Björheden, R., Gullberg, T. & Johansson, J. 2003. Systems analyses for harvesting small trees for forest fuel in urban forestry. *Biomass & Bioenergy 24(4-5)*: 389-400.

Björkman, C.A.T. 1877. *Handbok i Skogs-skötsel* [Manual for silviculture]. 2nd Ed. P.A. Norstedt förlag, Stockholm, Sweden. p. 95, 249-250, 255. (In Swedish).

Blackmore, S., Fountas, S., Have, H. 2002. Proposed System Architecture to Enable Behavioral Control of an Autonomous Tractor. In: Zhang, Q. (Ed). Automation Technology for Off-Road Equipment, Proceedings of the July 26-27, 2002 Conference, Chicago, Illinois, USA. *ASAE Publication No 701P0502*, St. Joseph, Michigan, USA. p. 13-23.

Bliss, J. & Martin, J. 1989. Identifying NIPF Management Motivations with Qualitative Methods. *Forest Science 35(2)*: 601-622.

Boman, M. & Ekenberg, L. 1999. *A survey of Decision Analysis and Risk Management.* Department of Computer and Systems Sciences, Royal Institute of Technology, Stockholm, Sweden. 27 p.

Brisette, J., Frank, R., Stone, T. & Skratt, T. 1999. Precommercial thinning in a northern conifer stand: 18-year results. *Forestry Chronicle 75(6)*: 967-972.

Brunberg, B. 1990. *Handledning i Röjning* [Manual for Cleaning]. Forskningsstiftelsen Skogsarbeten, Kista, Sweden. p. 6, 39-40. (In Swedish). ISBN: 91-7614-073-3.

Brunberg, B., Andersson, G., Nordén, B. & Thor, M. 1998. Uppdragsprojekt Skogsbränsle, slutrapport (Forest bioenergy fuel, final report of commissioned project Uppdragsprojekt Skogsbruk). *Redogörelse nr 6, SkogForsk*, Uppsala, Sweden. 60 p. (In Swedish with English summary). ISSN: 1103-4580.

Brooks, R.A. 1986. A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation* 2(1): 14–23.

Cain, M. & Shelton, M. 2003. Effects of alternative thinning regimes and prescribed burning in natural even-aged loblolly-shortleaf pine stands: 25year results. *Southern Journal of applied forestry 27(1)*: 18-29.

Canning, J.R., Edwards, D.B. & Anderson, M.J. 2004. Development of a fuzzy logic controller for autonomous forest path navigation. *Transactions of the ASAE 47(1)*: 301-310.
Carpelan, G. 1948. Motorsågar och deras användning i svenskt skogsbruk (Power-saws - their possibilities in Swedish Forestry). *Norrlands skogsvårdsförbunds tidskrift*. p. 227-290. (In Swedish with English summary).
Cawsey, A. 1997. *Essence of Artificial Intelligence*. Prentice-Hall, London, UK. p. 40-46. ISBN: 0-13-571779-5.
Clark, N.A., Wynne, R.H., Schmoldt, D.L. & Winn, M. 2000. An assessment of the utility of a non-metric digital camera for measuring standing trees. *Computers and electronics in agriculture 28(2)*: 151-169.
Daume, S., Füldner, K. & Gadow, K.v. 1997. Zur Modellierung personspezifischer Durchforstungen in ungleichaltrigen Mischbeständen (Modelling person specific thinnings in uneven-aged mixed stands). *Allgemeine Forst- und Jagdzeitung 169(2)*: 21-26. (In German with English summary).
Daume, S. & Robertson, D. 2000a. An architecture for the deployment of mobile decision support systems. *Expert Systems with Application 19(4)*: 305-318.
Daume, S. & Robertson, D. 2000b. A Heuristic Approach to Modelling Thinning. *Silva Fennica 34(3)*: 237-249.
Druzdzel, M. & Flynn, R. 2000. Decision Support Systems. In: Kent, A. (Ed.) *Encyclopedia of Library and Information Science, Volume 67, Supplement 30*, Marcel Dekker, New York, New York, USA. p. 120-133.
Ducey, M. 2001. Representing uncertainty in silvicultural decisions: an application of the Dempster-Shafter theory of evidence. *Forest Ecology and Management 150(3)*:199-211.
Durrant-Whyte, H. 2001. *A Critical Review of the State-of-the-Art in Autonomous Land Vehicle Systems and Technology.* Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550, USA.
Eisner, E. 1998. *The enlightened eye: Qualitative inquiry and the enhancement of educational practice.* Merrill, Prentice-Hall, Upper Saddle River, New Jersey, USA. p. 39, 201. ISBN: 0-13-531419-4.
Ek, B. 2003. Korridorröjning, otraditionellt och kostnadseffektivt [Strip cleaning, unconventional and cost effective]. *Skogen, nr 9*, p. 22-23. (In Swedish). ISSN: 0037-640X.
Eriksson, L. 1976. Konkurrensmodeller för enskilda träds tillväxt efter röjning. (Competition models for individual trees after cleaning.) *Rapporter och Uppsatser Nr 99, Department of Operational Efficiency, Royal College of Forestry,* Garpenberg, Sweden. p. 1-4, 16-17. (In Swedish with English summary).
Everitt, B. 2002. *The Cambridge dictionary of statistics*. 2nd Ed. Cambridge University Press, Cambridge, UK. p. 33, 86, 153, 366, 381. ISBN: 0-521-81099-X.
Fahlvik, N., Ekö, P.M. & Pettersson, N. 200X. Effects of different precommercial thinning strategies on a heterogeneous stand of Scots Pine, Norway spruce and birch. Manuscript, Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Uppsala, Sweden. 24 p. In: Aspects of precommercial thinning in heterogeneous forests in southern Sweden. *Acta Universitatis agriculturae Sueciae, 2005:68. Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences*, Alnarp, Sweden. ISBN: 91-576-6967-8
Forsman, P. 2001. Feature based registration of 3D perception data for indoor and outdoor map building. In: Halme, A., Chatila, R. & Prassler, E. (Eds.) *FSR2001 Proceedings of the 3rd International Conference on Field and Service Robotics, June 11-13, 2001, Finland.* Yleisjäljennös - Painopörssi, Helsinki, Finland. p. 367-372. ISBN: 952-5183-13-0.
Frohm S. 1996. Röjning -ett medel för god lönsamhet och förbättrad mångfald (Cleaning - an instrument for achieving high profitability and greater biodiversity). Utvecklingskonferens 96 (Research & Development Conference). *Redogörelse Nr 1, SkogForsk*, Uppsala, Sweden. p. 123-127. (In Swedish with English Summary).
Fryk, J. 1985. Skogsvårdsteknik - slutrapport från ett av Nordiska Skogsarbetsstudiernas Råd genomfört forskningsprojekt 1981-1984 (Silvicultural techniques - the final report of

a Nordic Research Council on Forest Operations (NSR) research project carried out between 1981 and 1984). *Redogörelse nr. 5, Forskningsstiftelsen Skogsarbeten*, Spånga, Sweden. p. 18-19 (In Swedish with English summary). ISSN: 0346-6671.

Füldner, K., Sattler, S., Zucchini, W. & Gadow, K.v. 1996. Modellierung personenabhängiger Auswahlwahrscheinlichkeiten bei der Durchforstung (Modelling person-specific tree selection probabilities in a thinning). *Allgemeine Forst- und Jagdzeitung 167(8)*: 159-162. (In German with English summary).

Gadow, K.v. & Füldner, K. 1995. Zur Beschreibung forstlicher Eingriffe (New ways of describing a thinning). *Forstwissenschaftliches Centralblatt 114(3)*: 151-159. (In German with English summary).

Gellerstedt, S. 1995. Robotik och informationsbehandling i skogliga produktionsmiljöer [Robotics and information processing in operational forest environments]. *Arbetsdokument, nr 1-version 2, Department of Operational Efficiency, Swedish University of Agricultural Sciences*, Garpenberg, Sweden. 27 p. (In Swedish).

Gellerstedt, S. 1997. Mechanised cleaning of young forest - The strain on the operator. *International Journal of Industrial Ergonomics 20(2)*: 137-143.

Gellerstedt, S., Moberg, L., Jansson, C.J., Asplund, C. & Herlitz, A. 1999. Automatiserad röjning, del 1 (Automated Mechanical Spacing of Young Stands of Forest, Part 1). *Research Note No. 4, Department of Forest Management and Products, Swedish University of Agricultural Sciences*, Uppsala, Sweden. 27 p. (In Swedish with English summary). ISSN: 1403-9516.

Giarratano, J. & Riley, G. 1998. *Expert Systems, Principles and Programming*. 3rd Ed. PWS Publishing Company, Boston, Massachusetts, USA. p. 1-14, 165-166. ISBN: 0-534-95053-1.

Glaser, B. & Strauss, A. 1967. *The Discovery of Grounded Theory, strategies for qualitative research*. Aldine de Gruyter, New York, USA. p. 66-67. ISBN: 0-202-30028-5.

Glöde, D. & Bergkvist, I. 2003. 30 år med maskinell röjning: summering av utförd FoU och analys av framtida potential (Thirty years of mechanized cleaning: a summary of the research and an analysis of future potential). *Redogörelse nr 4, SkogForsk,* Uppsala, Sweden. 37 p. (In Swedish with English summary). ISSN: 1103-4580.

Gustavsson, R. 1974. Typbestånd i röjningsskog (Type stands for cleaning). *Research Note No. 70, Department of Operational Efficiency, Royal College of Forestry*, Garpenberg, Sweden. 58 p. (In Swedish with English summary). ISSN: 0585-332X.

Gustavsson, R. & Moberg, L. 1975. Sammanställning över anordningar för mekanisk röjning [Compilation of tools for mechanical cleaning]. *Stencil nr 6, Department of Operational Efficiency, Royal College of Forestry*, Garpenberg, Sweden. p. 1. (In Swedish). ISSN: 0348-1972.

Hagner 1997. Professorns tips för bättre ekonomi, Röj för ökad ojämnhet [Advice from the Professor, clean for increased heterogeneity], *Skogseko, nr. 2*, p. 24-24. (In Swedish). ISSN: 0346-0495.

Have, H. 2002. Autonomous weeders for Christmas tree plantations - a feasibility study. *Pesticides Research Nr. 59, Danish Environmental Protection Agency, Danish Ministry of the Environment*, København, Denmark. 88 p. ISBN: 87-7972-135-4.

Hellström, T. 2002. Autonomous Navigation for Forest Machines, a Pre-Study. *UMINF 13, Department of Computing Science, Umeå University,* Umeå, Sweden. 60 p. ISSN: 0348-0542.

Hellström, T., Johansson, T., Ringdahl, O., Georgsson, F., Prorok, K. & Sandström, U. 2005. Development of an Autonomous Path Tracking Forest Machine. To be published in *FSR2005 Proceedings of the 5th International Conference on Field and Service Robotics, July 29-31 2005,* Port Douglas, Australia. Springer-Verlag STAR series.

Holmberg, L.E. 2005. Skogshistoria år från år 1177-2005 - skogspolitiska beslut och andra viktiga händelser i omvärlden som påverkat Skogsvårdsorganisationens arbete [Forest history year by year 1177-2005 - forest politics and other important events in the surroundings affecting the work of the forest administration]. *Rapport nr 5, Skogsstyrelsen,* Jönköping, Sweden. p. 17-19 (In Swedish). ISSN: 1100-0295. Available on the net at: www.svo.se/forlag/rapporter/1735.pdf (accessed 4-May-2005).

Holsapple, C. & Whinston, A. 1996. *Decision support systems, a knowledgebase approach.* West, Minneapolis/St. Paul, Minnesota, USA. 713 p. ISBN: 0-314-06510-5.

Hugosson, M. & Ingemarsson, F. 2004. Objectives and motivations of small-scale forest owners; theoretical modelling and qualitative assessment. *Silva Fennica 38(2)*: 217-231.

Håkansson M. & Steffen C. (Eds.). 1994. *PS Praktisk skogshandbok* [Practical forestry handbook]. 14th Ed. Sveriges Skogsvårdsförbund, Djursholm, Sweden. p. 67 (In Swedish). ISBN: 91-7646-030-4.

Häggström, B. 1955. Om hormonpreparat och deras användning [Regarding herbicides and their use]. *Norrlands skogsvårdsförbunds tidskrift*. p. 240-248. (In Swedish).

Högström, T. 1997. Making a forest out of trees – Methods for segmenting range images of forest environments. In: Tele-commands for Semi Autonomous Control in Tele-robotics. *Licentiate Thesis No. 624, Linköping University,* Linköping, Sweden. p. 63-92. ISBN: 91-7871-963-1.

Hörnsten, L. 2000. Outdoor recreation in Swedish forests - implications for society and forestry. *Acta Universitatis agriculturae Sueciae, Silvestria 169, Swedish University of Agricultural Sciences,* Uppsala, Sweden. 29 p. ISBN: 91-576-6053-0.

Jansson, O. 2001. Forskare och bolag om framtidens skogsbruk: många steg att ta innan vi når en förarlös skotare [Researchers and companies regarding future forestry: a long way to go before unmanned forwarders are reality]. *Tidningen skogsteknik, nr 4*, p. 42-44. (In Swedish). ISSN: 1650-8092.

Johansson, S. 2000. Högt spel med fina ungskogar [Qualitative young forests at risk]. *Skogen, nr 11*. p. 44-47. (In Swedish). ISSN: 0037-640X

Kahle, M. 1995. Die analyse von Eingriffsentscheidungen in einem Buchen-Edellaubholz-Mischbestand [Analysis of selections in thinning of a deciduous stand]. Diplomarbeit, Forstliche Fakultät, Georg-August-Universität, Göttingen, Germany. p. 28. (In German).

Kahn, M. 1995. Die Fuzzy Logik basierte Modellierung von Durchforstungseingriffen (Modelling thinning regimes with a fuzzy logic controller). *Allgemeine Forst- und Jagdzeitung 166(9-10)*: 169-176. (In German with English summary).

Kaivola, A. 1996. Trends in the tending of young stands and its mechanisation in Finland. In: Berg, S. (Ed.). Site preparation and stand treatment - impact on biology, economy and labour. Proceedings of S.3.02-00 Technical sessions during IUFRO XX World Congress 1995, held in Tampere, Finland, Selected papers. *Report No 2, SkogForsk,* Uppsala, Sweden. p. 176-188. ISSN: 1103-6648.

Kangas, AS. & Kangas, J. 2004. Probability, possibility and evidence: approaches to consider risk and uncertainty in forestry decision analysis. *Forest policy and economics 6(2)*: 169-188.

Kardell, L. 2004. *Svenskarna och skogen, del 2, Från baggböleri till naturvård* [The Swedes and the forest, part 2, from Baggböleri to environment protection]. Skogsstyrelsens förlag, Jönköping, Sweden. p. 17-32, 175-177. (In Swedish). ISBN: 91-88462-57-9.

Karlsson, F. 200X. Privata markägares reflektioner med hänseende till den minskande röjningsaktiviteten, så kan Skogsvårdsstyrelsen anpassa sitt arbete [NIPF owners thoughts regarding the decreasing cleaning activity, in this way the regional forestry boards can adjust their work]. Manuscript for undergraduate thesis presented on the 8th of June 2005. To be published as *Examensarbeten, No XX, Department of Forest Products and Markets, Swedish University of Agricultural Sciences*, Uppsala, Sweden. (In Swedish with English summary). ISSN: 1651-4467.

Karlsson, H., Lundmark, J., Sundkvist, H., Wahlgren, B., Jacobsson, J. & Johansson, O. 1997. *Röjningshandbok, virkeskvalité - ståndortsanpassning - naturvård* [Cleaning manual, wood quality - site adaptation - nature conservation]. AssiDomän Skog & Trä, Stockholm, Sweden. p. 11, 39-55. (In Swedish).

Keeney, R. & Raiffa, H. 1993. *Decisions with multiple objectives, preferences and value tradeoffs*. 2nd Ed. Cambridge University Press, Cambridge, UK. p. 31-69. ISBN: 0-521-44185-4.

Keicher, R. & Seufert, H. 2000. Automatic guidance for agricultural vehicles in Europe. *Computers and electronics in agriculture 25(1-2)*: 169-194.

Kourtz, P. 1996. Autonomous forestry robots for brushing and thinning in young conifer stands: early Canadian experiences. In: Gellerstedt, S., Asplund, C. & Wästerlund, I., (Eds.) Robotics with application to forestry. *Uppsatser och resultat Nr. 285, Department of Operational Efficiency, Swedish University of Agricultural Sciences*, Garpenberg, Sweden. p. 25-38. ISSN: 0282-2377.
Kurabyashi, D. & Asaman, H., 2001. Navigation method by distributed map management for autonomous bush removal robot. In: Halme, A., Chatila, R. & Prassler, E. (Eds.) *FSR2001 Proceedings of the 3rd International Conference on Field and Service Robotics, June 11-13, 2001, Finland.* Yleisjäljennös - Painopörssi, Helsinki, Finland. p. 361-366. ISBN: 952-5183-13-0.
Ladrach, W. 2004. Harvesting and comparative thinning alternatives in Gmelina arborea plantations. *New Forests 28(2-3)*: 255-268.
Lehnbom, J. & Larsson, P. 2003. *Simulering av ungskog* [Simulation of Young Forests]. Institutionen för matematik, natur- och datavetenskap, Högskolan i Gävle, Gävle, Sweden. 19 p. (In Swedish).
Lidén, E. 1995. Inquiries into harvesting systems, quantities, and machine ownership in Swedish industrial forestry - status 1985/86 and 1992/93 and prediction for 1997/98. *Uppsatser och resultat 273, Department of operational efficiency, Swedish University of Agricultural Sciences,* Garpenberg, Sweden. p. 7-8, 11. ISSN: 0282-2377.
Lidestav, G. & Nordfjell, T. 2002. *Med skogsägaren i fokus* [Focusing on the forest owner]. LRF Skogsägarna, Sweden. 56 p. (In Swedish).
Ligné, D. 1999. Sammanställning av patent och principer rörande röjning (Compilation of patents and principles concerning cleaning). *Students' Reports No 24, Forest Technology, Swedish University of Agricultural Sciences*, Umeå, Sweden. p. 1-2. (In Swedish with English summary).
Ligné, D. 2004. New technical and alternative silvicultural approaches to pre-commercial thinning. *Acta Universitatis agriculturae Sueciae, Silvestria 331, Swedish University of Agricultural Sciences,* Umeå, Sweden. 46 p. ISBN: 91-576-6715-2.
Ligné, D., Nordfjell, T. & Karlsson, A. 200X. New techniques for pre-commercial thinning – time consumption and tree damage parameters. (Accepted for publication in *International Journal of forest engineering*, ISSN: 1494-2119).
Lindman, J. 1987. Maskinell röjning - en presentation [Mechanical Cleaning - a presentation]. *Resultat Nr. 2, Forskningsstiftelsen Skogsarbeten*, Spånga, Sweden. 4 p. (In Swedish). ISSN: 0280-1884.
Lloyd, T. & Waldrop, T. 1999. Backburning as an alternative to traditional pre-commercial thinning. *Tree Farmer: The Practical Guide to Sustainable Forestry, May/June*. p.16, 36. Available on the net at: www.srs.fs.usda.gov/pubs/ja/ja_lloyd001.pdf (accessed 4-Mar-2005).
Marchant, J.A., Hague, T. & Tillett, N.D. 1997. Row-following accuracy of an autonomous vision-guided agricultural vehicle. *Computers and electronics in agriculture 16(2)*: 165-175.
Magnusson, D. 1978. On the human limitations. *Supplement no 43, Report from the Department of Psychology, University of Stockholm*, Stockholm, Sweden. 15 p. ISSN: 0345-021X.
Mattsson, S. & Westerberg, D. 1992. Röjmaskiner i praktisk drift [Cleaning machines in operational use]. *Resultat Nr. 5, SkogForsk*, Uppsala, Sweden. 4 p. (In Swedish). ISSN: 1103-4173.
Mellström, C. & Thorsén, Å. 1981. Lövröjning med Jörns röjaggregat monterat på Bruunett Mini skotare, Tidsstudier utförda vid Domänverket december 1980 och april 1981 [Cleaning deciduous stands with Jörns' cleaning tool mounted on a Bruunett Mini forwarder, Time-studies made at Domänverket in December 1980 and April 1981]. *Stencil 1981-05-15, Forskningsstiftelsen Skogsarbeten*, Stockholm, Sweden. p. 1. (In Swedish).
Mendoza, G. & Sprouse, W. 1989. Forest Planning and Decision Making under Fuzzy Environments: An Overview and Illustration. *Forest Science 35(2)*: 481-502.

Menger, K. 1934. Das Unsicherheitsmoment in der Wertlehre [The Role of Uncertainty in Economics]. *Zeitschrift für Nationalökonomie 5*: 459-485. (In German). ISSN: 0044-3158.

Mills, W.L. 1987. Expert systems in forest resources management. In: Dress, P. & Field, R. (Eds.). *The 1985 Symposium on system analysis in forest resources, The Georgia center for continuing education, Athens, Georgia, December 9-11 1985.* Georgia center for continuing education, Athens, Georgia, USA. p. 349-362.

Myhrman, D. 1987. Maskiner för maskinell röjning [Machines for mechanical cleaning]. *Resultat Nr 5, Forskningsstiftelsen Skogsarbeten*, Spånga, Sweden. 4 p. (In Swedish). ISSN: 0280-1884.

Mäkinen, H. 1996. Effect on Intree Competition on Branch Characteristics of Pinus sylvestris Families. *Scandinavian Journal of Forest Research 11(2)*: 129-136.

Möller-Madsen, E. & Petersen, H.C. 2002. Udrensning i meget planterige bøgeforyngelser [Cleaning of very dense beech regenerations]. *DST, Dansk Skovbrukgs Tidsskrift nr 87*. p. 109-130. (In Danish). ISSN: 0905-295X.

Nielsen, H. & Fountas, S. 2002. Autonomous vehicle technology - a literature review. In: Have, H. (Ed.) Autonomous weeders for Christmas tree plantations - a feasibility study. *Pesticides research no. 59, Danish Environmental Protection Agency, Danish Ministry of the Environment,* København, Denmark. p. 34-43. ISBN: 87-7972-135-4.

Nilsson, P. & Gustafsson, K. 1999. Skogsskötseln vid 90-talets mitt -läge och trender [Silviculture in the mid 90s - state and trends]. *Arbetsrapport 56, Department of forest resource management and geomatics, Swedish University of Agricultural Sciences*, Umeå, Sweden. p. 23. (In Swedish). ISSN: 1401-1204.

Noguchi, N., Reid J., Will J., Benson, E. & Stombaugh, T. 1998. Vehicle automation system based on multi-sensor integration. *UILU-ENG-98-7021, An ASAE Meeting Presentation, Paper 983111 ASAE,* St. Joseph, Michigan, USA. 12 p.

Nordansjö, I. 1988. Teknisk utveckling i skogsbruket 1938-1988 (Technological advances in forestry, 1938-1988). In: Skogsteknisk forskning och utveckling i Sverige under 50 år (50 years of forest technology R & D in Sweden). *Redogörelse no 6, Forskningsstiftelsen Skogsarbeten*, Kista, Sweden. p. 5, 25-38. (In Swedish with English summary). ISSN: 0346-6671.

Normark, E., & Bergqvist, G. 2000. *Röjningshandledning* [Cleaning manual]. Holmen Skog, Örnsköldsvik, Sweden. p. 4-7, 10-11. (In Swedish).

Nåbo, A. 1992. Systems design in planting operations, a method for concept development applied to planting operations in forestry. *Research notes no. 233, Dept. of Operational Efficiency, Swedish University of Agricultural Sciences*, Garpenberg, Sweden. p. 10. ISSN: 0282-2377.

Partridge, D. 1998. *Understanding the Promise of the Future*. Artificial Intelligence and Software Engineering, Glenlake Publishing, Chicago, USA. 274 p. ISBN: 1-888998-36-9.

Patton, M. Q. 1990. *Qualitative Evaluation and Research Methods*. 2nd Ed. Sage Publications Newbury Park, California, USA. p. 172, 184, 196, 280-281, 283-284, 360-362. ISBN: 0-8039-3779-2.

Pettersson, B. 1973. Kan röjningen förbättras? [Can cleaning be improved?]. *Ekonomi nr 7, Forskningsstiftelsen Skogsarbeten*, Stockholm, Sweden. 4 p. (In Swedish).

Pettersson, B. & Bäcke, J. 1998. Röjningsundersökning 1997, Produktion - Miljö [Cleaning inventory 1997, Yield - Environment]. *Meddelanden Nr 7, Skogsstyrelsen*, Jönköping, Sweden. 18 p. (In Swedish). ISSN: 1100-0295.

Pettersson, F. 2001. Effekter av olika röjningsåtgärder på beståndsutvecklingen i tallskog (Impact of different cleaning regimes on the development of Scots-pine stands). *Redogörelse, nr 4. SkogForsk*, Uppsala, Sweden. 28 p. (In Swedish with English summary). ISSN: 1103-4580.

Pettersson, N. 1986. Korridorröjning i självsådd tallungskog (Line thinning in young natural regenerated pine stands). *Rapport 17, Department of forest yield research, Swedish University of Agricultural Sciences,* Garpenberg, Sweden. 21 p. (In Swedish with English summary). ISBN: 91-576-2646-4.

Pettersson, N. 1993. The effect of density after precommercial thinning on volume and structure in Pinus-sylvestris and Picea-abies stands. *Scandinavian Journal of Forest Research 8(4)*: 528-539.
Pitt, D., Morneault, A., Bunce, P. & Bell, W. 2000. Five years of vegetation succession following vegetation management treatments in a Jack Pine ecosystem. *Northern Journal of Applied Forestry 17(3)*: 100-109.
Reid, J. F. 1998. Precision Guidance of Agricultural Vehicles. *UILU-ENG-7031, Japanese Society of Mechanical Engineering, Meeting September 1998*, Sapporo, Japan. 10 p.
Rennerfeldt, E. 1948. Försök att med kemiska medel förhindra stubbskottsbildning hos björk på hyggen [Experiments with herbicides to prevent birch sprout at clear-felled areas]. *Norrlands skogsvårdsförbunds tidskrift*. p. 119-139. (In Swedish).
Russell, S. & Norvig, P. 1995. *Artificial Intelligence, a modern approach*. Prentice Hall, Englewood Cliffs, New Jersey, USA. p. 31-50. ISBN: 0-13-360124-2.
Ryans, M. 1988. Mechanized precommercial thinning methods: experience to date. *Special Report, SR-56, Forest engineering research institute of Canada (FERIC)*, Pointe Claire, Quebec, Canada. p. 11. ISSN: 0381-7733.
Ryans, M. & St-Amour, M. 1996. Mechanized systems for early stand tending in central and eastern Canada. In: Berg, S. (Ed.). Site preparation and stand treatment - impact on biology, economy and labour. Proceedings of S.3.02-00 Technical sessions during IUFRO XX World Congress 1995, held in Tampere, Finland, Selected papers. *Report No 2, SkogForsk*, Uppsala, Sweden. p. 189-198. ISSN: 1103-6648.
Rydberg, D. 1992. Skog i stad [Forest in the city]. *Skog&Forskning, nr 4*. p. 44-51. (In Swedish). ISSN: 1101-9506.
Scott, R. 2003. *Organizations - rational, natural, and open systems*. 5th Ed. Prentice-Hall, Upper Saddle River, New Jersey, USA. p. 255-257. ISBN: 0-13-121803-4.
Siddall, J. 1972. *Analytical decision-making in engineering design*. Prentice-Hall, Englewood Cliffs, New Jersey, USA. p. 17. ISBN: 0-13-034538-5.
Simon, H. 1995. Artificial intelligence: an empirical science. *Artificial Intelligence 77(1)*: 95-127
St-Amour, M. 2004. Semi-mechanized precommercial strip thinning - observations of a two-row method using the Nokamic NP-540 brushcutter. *Advantage, Volume 5, No. 32, Forest engineering research institute of Canada (FERIC)*, Pointe-Claire, Quebec, Canada. 8 p. ISSN: 1493-3381.
Stentz, A. 2001. Robotic Technologies for Outdoor Industrial Vehicles. In: *Proceedings of SPIE AeroSense April 2001, Conference on Unmannded Robotic Vehicles*, Orlando, Florida, USA. 8 p.
Strauss, A. & Corbin, J. 1990. *Basics of qualitative research: Grounded theory procedures and techniques*. Sage Publications, Newbury Park, California, USA. p. 19, 30, 42-43. ISBN 0-8039-3250-2.
Strobl, S. & Bell, W. 2000. Vegetation management for individual tree control. In: *A Silvicultural Guide to Managing Southern Ontario Forests*. Ministry of Natural Resources, Ontario, Canada. p. 339-360. Available on the net at: www.ont-woodlot-assoc.org/silvic/index.htm (accessed 4-Mar-2005).
Synwoldt, U. 2001. The Swedish Work Environment Authority and its initiatives relating to the work environment in Swedish forestry. *Acta Universitatis agriculturae Sueciae, Silvestria 186, Swedish University of Agricultural Sciences*, Uppsala, Sweden. p. 35. ISBN: 91-576-6070-0.
Tarp-Johansen, M.J. 2001. Locating individual Trees in Even-aged Oak Stands by Digital Image Processing of Aerial Photographs. *PhD Thesis, Royal Veterinary and Agricultural University*, Copenhagen, Denmark. 158 p.
Tham, Å. 1987. Är korridorröjning i tallungskog lönsamt? [Can strip cleaning be profitable?] *Teknik i Jord & Skog, nr 4*. p. 47-48. (In Swedish). ISSN: 0282-8618.
Thorner, M. 2004. Ny teknik i skogen: nästa besparing - färre maskinförare [New technology in the forest: the next saving - fewer machine operators]. *Tidningen skogsteknik, nr 1*. p. 8-9. (In Swedish). ISSN: 1650-8092.
Tillett, N. 1991. Automatic Guidance Sensors for Agricultural Field Machines -a review. *Journal of agricultural engineering research 50(3)*: 167-187.

Tosterud, A. & Bergqvist, S. 1990. Makinell röjning och lagarbete -en konst att introducera [Mechanical cleaning and team-work - the art of introducing]. *Resultat nr 17, Forskningsstiftelsen Skogsarbeten*, Kista, Sweden. 4 p. (In Swedish). ISSN: 0280-1884.

Tong, Q.J., Zhang, S.Y. & Thompson, M. 2005. Evaluation of growth response, stand value and financial return for pre-commercially thinned jack pine stands in Northwestern Ontario. *Forest Ecology and Management 209(3)*: 225-235.

Uhlin, T. & Johansson, K. 1996. Autonomous mobile systems. *Trita-NA-P 9603, Department of Numerical Analysis and Computing Science, Royal Institute of Technology, Stockholm University,* Stockholm, Sweden. p. 3-4, 17. ISSN: 1101-2250.

Wahlgren, A. 1914. *Skogsskötsel, handledning vid uppdragande, vård och föryngring av skog* [Silviculture, manual for nursing, tending and regeneration of forests]. P.A. Norstedt & Söners förlag, Stockholm, Sweden. p. 222-223. (In Swedish).

Varmola, M. & Salminen, H. 2004. Timing and intensity of precommercial thinning in Pinus sylvestris stands. *Scandinavian Journal of Forest Research 19(2)*: 142-151.

Waterman, D. 1985. *A guide to expert systems*. Addison-Wesley Publishing Company, Teknowledge series in knowledge engineering, Reading, Massachusetts, USA. p. 18. ISBN: 0-201-08313-2.

Vestlund, K. 2001a. Autonom röjning, förutsättningar (Autonomous Cleaning of Young Forest Stands, Conditions). *Report No. 12, Department of Forest Management, Swedish University of Agricultural Sciences*, Uppsala, Sweden. 39 p. (In Swedish with English summary). ISSN: 1403-9516.

Vestlund, K. 2001b. Redovisning av intervjuer med tre personer som utför ungskogsröjning (Report of Interviews with three Persons performing Cleaning and Spacing in Young Forest Stands). *Report No. 14, Department of Forest Management, Swedish University of Agricultural Sciences*, Uppsala, Sweden. 15 p. (In Swedish with English summary). ISSN: 1403-9516.

Vestlund, K. 2003. First steps to a computer based selection of trees in practical cleaning. In: Iwarsson-Wide, M. & Hallberg, I. (Eds.). Proceedings, posters: technique and methods, 2nd forest engineering conference, 12-15 may 2003, Växjö, Sweden. *Arbetsrapport 539, SkogForsk*, Uppsala, Sweden. p. 58-61. ISSN: 1404-305X.

Wilson, J.N. 2000. Guidance of agricultural vehicles - a historical perspective. *Computers and electronics in agriculture 25(1-2)*: 3-9.

Zhang, Q., Reid, J. & Noguchi, N. 1999. Agricultural vehicle navigation using multiple guidance sensors. Proceedings of the International Conference on Field and Service Robotics, August 29-31, Pittsburgh, Pennsylvania, USA. *UILU-ENG-99-7013, The Robotics Institute at Carnegie Mellon University,* Pittsburgh, Pennsylvania, USA. 6 p.

Zimmerman, K.G. 1948. Organisationen av motorsågarnas användning -några erfarenheter från fällning med tvåmanssåg i Mellan Sverige (The organization of power-saw felling - some experiences from two-man power-saw felling in Central Sweden). *Norrlands skogsvårdsförbunds tidskrift*. p. 394-416. (In Swedish with English summary).

Zucchini, W. & Gadow, K. v. 1995. Two Indices of Agreement among Foresters Selecting Trees for Thinning. *Forest & landscape research 1995(1)*: 199-206.

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Swedish summary

Aspekter på automation av selektiv röjning

Röjning är en beståndsvårdande åtgärd som minskar antalet stammar i skogsbestånden så att tillväxtmöjligheterna förbättras för kvarstående stammar. Mekaniseringen av skogsbruket var under förra seklet omfattande, framförallt inom avverkningsarbetet. Inom skogsvården har dock utvecklingen inte varit lika genomgripande. Röjmotorsågen introducerades under 1950-talet och försök att mekanisera röjningen skedde under 1970- och 80-talen, men mekaniserad röjning har hitintills totalt sett visat osäker lönsamhet samt skapat stressig förarmiljö. Idag finns därför knappast någon röjningsmaskin i drift utan röjning utförs alltjämt med röjmotorsåg och är således en personalintensiv åtgärd. I Sverige anses röjning vara dyrt och det förekommer svårigheter att rekrytera personal till det ansträngande arbetet vilket återigen har ökat intresset att mekanisera arbetet. Terränggående autonoma robotar kan också vara en lösning men då krävs nya kunskaper. Med autonom menas att ”föraren” inte ska styra maskinen direkt utan arbetsleda en eller flera maskiner.

Målen med denna avhandling var att analysera centrala problemställningar rörande automation av röjning, samt att presentera förslag på lösningar med fokus på automatisering av stamvalsprocessen.

Litteraturstudier användes för att formulera de krav och önskemål som finns på automatiserat röjningsarbete. Förslagen på lösningar och hjälpmedel som kan nyttjas i skogligmiljö bygger också på litteraturstudier men även fältförsök med laserscanner. Kvalitativa intervjuer genomfördes med personer som arbetar med röjning (röjare) för att skaffa kunskap om hur stamval och övrigt arbete sker idag. Röjningsmanualer och kunskaperna från intervjuerna tillsammans med fältinventeringar användes för att utveckla ett datoriserat beslutsstöd för automatiskt stamval. Detta beslutsstöd användes sedan för att köra datorbaserade röjningar (simuleringar) i olika skogstyper. Resultaten av dessa simuleringar utvärderades först på traditionellt sätt avseende stammar per hektar, andel löv och andel skadade träd i det kvarvarande beståndet. Därefter fick röjare ”röja” (ange på en karta valda träd i beståndet) och en jämförelse av deras resultat och simuleringsresultaten gjordes. I en tredje utvärdering fick några lekmän ”röja” med hjälp av beslutsstödet.

De viktigaste kraven framtida röjningsrobotar måste uppfylla är kostnads-effektivitet samt att producerade resultat som når en nivå som uppdragsgivarna godtar. De måste även vara tillförlitliga och säkra, dvs kunna arbeta dygnet och året runt självständigt utan kontinuerlig tillsyn under flera timmar i föränderlig och okänd skogsmiljö utan att haverera eller skada djur, människor och kvarstående skog. Röjningsrobotarna måste kunna navigera och lokalisera sig automatiskt samt finna, välja och behandla träd i hela beståndet i enlighet med givna instruktioner. Maskinellt seende samt radar- och lasersensorer är möjliga tekniker för att ta sig fram i terrängen, identifiera stammar och kontrollera röjningsaggregatet. I bilder producerade med data från en laserscanner var det möjligt att hitta träd och mäta deras höjd och diameter. Dock blev resultaten från den genomförda studien inte helt korrekta eftersom toppen av träden missas och delar av grenar klassificeras som stam. Ovan nämnda typer av sensorer kan troligen också användas för att skydda omgivningen men därtill behövs bl a lutningsmätare för att skydda maskinen från haveri. Kostnaderna kan förhoppningsvis hållas nere om lösningar från t ex multimedia och bilindustrin kan nyttjas. Det finns autonoma system utvecklade inom andra områden och några relativt små skogsmaskiner som är intressanta för vidareutveckling och det finns även ett röjningsaggregat som skulle kunna användas. Förutom hårdvara krävs mjukvara. I avhandlingen presenterades en mjukvaruarkitektur som behandlar hur arbetsmomenten i röjning kan utföras, innehållande bl a Uppdragsplanerare, Sekventierare, Kartritare, Resurshanterare och Uppdragshanterare.

Stamval är ett kritiskt steg i automatiseringsprocessen och för att skapa datorbaserade röjningsregler måste dagens röjningsmanualer kombineras med röjarnas tysta kunskap. Intervjuerna visade att instruktionerna som röjarna ges ofta är schablonartade vilket gör att de till stor del själva avgör hur arbetet ska utföras. Erfarna röjare anger att valet sker ”automatiskt” medan oerfarna röjare kan behöva tänka en kort stund. Tiden för valet är dock begränsad och röjarna upplever att tidspressen har ökat eftersom betalningen legat still de senaste tio åren. Detta gör att de hela tiden ser sig om i beståndet för att värdera träden. Då oerfarna röjare känner stressen att producera röjda arealer medför det att de oftare lämnar för många träd och de kan ha svårare att se skador på träden. Dessutom kan de behöva mer handledning. Oavsett erfarenhet tittar dock röjarna på liknande karaktäristika för att välja stam men deras regler för stamval är oklara. De föredrar raka friska stammar av rätt trädslag och med rätt storlek och position i förhållande till övriga stammar, men även andra stammar som inte uppfyller dessa krav måste lämnas för att antalet stammar per hektar inte ska bli för få. Vid jämförelse av röjarnas implicita ”regler” och publicerade instruktioner märks tydliga skillnader när det gäller önskat stamantal och tillåten höjd på kvarvarande småstammar. Det finns även skillnader beträffande oönskade egenskaper. Uppföljning av gjorda röjningar är ganska generell och det är sällan röjarna får ta del av den. Uppdragsgivaren och röjarna har idag inte mycket kontakt. Tidigare ordnade skogsbolagen utbildningsdagar då röjare fick direkt respons av en expert på utförd röjning. Erfarna röjare säger sig inte sakna denna typ av återkoppling, men bristen på respons gör att röjarna får svårt att veta om deras resultat är bra eller dåligt vilket också gör att de får svårt att lära sig av erfarenhet. Således kan och bör stamvalen inte baseras på röjarnas implicita ”regler” utan istället baseras på de trädegenskaper som röjarna och röjningsmanualerna återkommer till.

Det utvecklade beslutsstödet använder egenskaperna trädslag, position, diameter och skada för att välja stammar. Eftersom sikten i bestånden vanligen är runt fem meter arbetar beslutsstödet med data inom en avgränsad yta. I stora drag väljs i första hand önskvärda träd inom en yta, men även andra träd kan tillåtas för att målen om stamantal och lövandel i hela beståndet ska kunna uppnås. Resultatet av sex simuleringar med olika inställningar i beslutsstödet visar att beståndens ursprungliga tillstånd påverkar resultaten men att målen generellt kan nås. I genomsnitt skilde stamantalet från målvärdet med -20 % till +6 %. Lövandelen ändrades mot målvärdet och andelen skadade minskade från 14–90 % till 4–13 % efter de simulerade röjningarna. Medeldiametern ökade med 40–56 % efter de olika simuleringarna och minimiavståndet mellan stammar överskreds aldrig. Denna traditionella utvärdering visar att beslutsstödet fungerar och att den verkar ge acceptabla resultat i flera typer av skog.

Vid en jämförelse mellan röjare och två simuleringar, en generell och en som anpassats för att likna röjarnas resultat, visade det sig att resultaten påverkades mer av bestånden än av huruvida röjningen utförts av röjare eller dator. Skadeandelen och lövandelen påverkades av lokalen och röjarna hade högre skade- och lövandel än den ”generella” simuleringen. Beslutsstödet väljer dock till mer än 80 % samma stammar som minst en av röjarna. Lekmännen fick ett mycket homogent resultat när de använde beslutsstödet. Dessa ytterligare utvärderingar av beslutsstödet visar att det verkar vara användbart, flexibelt och robust. Det kan anpassas så att det ger resultat som liknar röjarnas och det kan användas som ett objektivt hjälpmedel vid motormanuell röjning. För att användas av människor bör dock beslutsstödets användarvänlighet förbättras. I detta fall kan även andra attribut än de valda användas då inget krav finns att de valda attributen måste kunna mätas automatiskt.

Kommer framtidens ungskogsröjning att utföras av robotar? Kanske, men det är en lång väg kvar att gå. Fördelarna med ett autonomt röjningssystem måste upplevas så stora att man är beredd att satsa på utvecklingsarbete. Några av de autonoma maskiner som utvecklats för andra ändamål bör kunna vidareutvecklas till arbetsmaskiner för skogsbruket, men för att detta ska kunna ske krävs både resurser och tvärvetenskaplig forskning. Troligen krävs även en uttalad önskan från skogsbolagen för att en förändring ska komma till stånd. De viktigaste kraven framtida röjningsrobotar måste uppfylla är att kostnadseffektivt producera godtagbara resultat, och det måste ske på ett tillförlitligt och säkert sätt. Det är även viktigt att en framtida röjningsrobot anpassas till den omgivning den ska verka i, dvs den organisation av maskiner och människor som redan finns. Därtill måste alla delar av röjningsarbetet beskrivas ur ett robotperspektiv, och att implementera autonoma funktioner till en robot är komplicerat.

Om/När ett autonomt röjningssystem införs kommer arbetsorganisationen att påverkas, men resultaten av röjningarna ska inte få påverkas (åtminstone inte negativt). Det är därför viktigt att stamvalet automatiseras och ett datorbaserat beslutssystem konstrueras. Målet med det i avhandlingen presenterade beslutstödet var framförallt att skapa ett operationellt automatiskt system som ger resultat som liknar de resultat erfarna röjare presterar. Beståndens initiala tillstånd påverkar möjligheten att nå de uppställda målen gällande bl a stamantal och lövandel i beståndet, men utvärderingar visar att beslutsstödet generellt ger acceptabla resultat. Inställningarna i beslutsstödet måste dock anpassas både till beståndet och till skogsägarens/uppdragsgivarens önskemål. Att använda beslutsstödet för autonom eller semiautonom röjning är möjligt, men först när de valda trädegenskaperna kan mätas automatiskt. Beslutsstödet bör dock redan nu kunna användas som ett objektivt hjälpmedel i traditionell motormanuell röjning.