Timber harvester operators' working technique in first thinning and the importance of cognitive abilities on work productivity

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Academic dissertation

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ABSTRACT

The working environment of timber harvester operators has changed dramatically over the past fifteen years. The operator's physical workload has decreased while the proportion of mental load has increased, as a consequence of the increased responsibilities involved in the cutting work. The decision making during the work has also increased and speeded up considerably. Therefore, the importance of the operator, with regards to harvester productivity, has been emphasized as a result of the equalization of the different harvester brands. For this reason, more and more attention is paid to the operator with the expectation of reaching certain productivity levels. This also places extra expectations on the operator's training; especially in demanding cutting conditions, such as in first thinning, where the operator's abilities are tested the most.

The principal objective of this research was to discover and describe a productive working technique for harvester work in first thinning and to improve harvester operator training by highlighting the problems of harvester simulators and determining the important cognitive abilities needed in harvester work. The work of six professional harvester operators was studied using numerous data collection methods: time study, working technique observation, helmet camera video recording, virtual harvester simulator cutting and psychological tests. In addition, 40 harvester operator students participated in the psychological tests.

The results indicated that when working productively, in first thinning conditions, the moving distance of the harvester head is minimized. In positioning the harvester head to a removable tree the positioning distance should be short. In felling a removable tree, the tree should be moved only the distance that fluent boom work necessitates. The work should be planned so that reversing is avoided and non-productive time, such as clearing of small trees, is minimal. From the fluent boom working point of view the results showed the operators' consistent method to locate the harvester optimally according to the edge trees of the strip road. Based on this a productive working technique for harvester work in first thinning was created and described. A productive working technique can increase productivity by 10 to 15%. In addition, the handling of trees located in different places around the harvester was theorized. The results also indicated that the virtual harvester simulators are applicable for harvester training when the trainees are conscious of the limitations of the simulators. From the point of view of harvester operator training and operator selection the psychological tests indicated that productive and skilful harvester operating is not solely explained by one cognitive ability, instead, the mastering of different kinds of abilities appears to be more important. By combining the productive working technique with the operator training and taking into account the cognitive challenges faced in harvester work, for example, work planning and perception, the graduated students are likely to be more productive and ready to meet the challenges of working life.

Keywords: single-grip harvester, time study, method study, work study, Ripley's K, psychological testing, operator education

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LIST OF ORIGINAL ARTICLES

The thesis is based on original articles I-IV.

I   Ovaskainen, H., Uusitalo, J. & Väätäinen, K. 2004. Characteristics and significance of a harvester operators' working technique in thinnings. International Journal of Forest Engineering 15(2): 67–77.

II   Ovaskainen, H. 2005. Comparison of harvester work in forest and simulator environments. Silva Fennica 39(1): 89–101.

III   Ovaskainen, H., Uusitalo, J. & Sassi, T. 2006. Effect of edge trees on harvester positioning in thinning. Forest Science 52(6): 659–669.

IV   Ovaskainen, H. & Heikkilä, M. 2007. Visuospatial cognitive abilities in cut-to-length single-grip timber harvester work. International Journal of Industrial Ergonomics 37(9-10): 771–780.

Study I: Ovaskainen and Väätäinen planned the data collection and collected the data. Ovaskainen calculated, analyzed and wrote the article with comments and help of Väätäinen. Uusitalo helped in writing the manuscript. Ovaskainen submitted the article.

Study III: Ovaskainen and Sassi created the idea of the article. Ovaskainen collected the data, analyzed the results, wrote most of the manuscript and submitted the article. Uusitalo commented and contributed in writing the article.

Study IV: Heikkilä selected and planned tests, executed testing and calculated the data. Ovaskainen tested the data with statistical tests and wrote most of the manuscript, with contributions from Heikkilä. Ovaskainen submitted the article.

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1 INTRODUCTION

1.1 Productivity

A higher standard of living is a desirable goal. The greater the amount of goods and services produced in a community, the higher its average standard of living. There are two ways of increasing the amount of goods and services produced; increase employment or increase productivity (ILO 1981). Employment can be increased by governmental labor decisions at a national level, while the increment in productivity can be reached with smaller efforts by companies even on a worker level.

Productivity is generally defined as ratio of output to input, in other words, the arithmetical ratio between the amount produced and the amount of any resource used in the course of production (ILO 1981). Consequently, in theory, higher productivity can be reached by increasing the output while the input remains the same or lowering the input while the output remains the same or changing both output and input. When considering productivity of work performed with a tool, such as a machine, time needs to be taken into account in the ratio, since it is usually the output to production in a given time. In machine work, productivity is frequently measured as the output in a machine-hour (Samset 1990).

Nowadays, forest harvesting is highly mechanized in Finland; in 2006 up to 98% of the wood harvested was with machines (Nouvo 2007). In the normal Nordic cutting method, cut-to-length (CTL) method, single-grip timber harvesters are widely used for felling, delimbing and crosscutting trees into logs at the stump for maximizing the stem value. A typical harvester is equipped with a parallel crane with a harvester head used for both thinning and clear cutting areas, bogie axels in the front, a rigid axle in the back, as well as a cab, and advanced CAN-based measuring and control system that monitors, measures and controls tree processing. In harvester work, productivity is typically measured in processed cubic meters of raw wood per effective hour (m^3/h_0), which is influenced by numerous varying factors.

1.2 Factors affecting productivity in harvester work

1.2.1 General

The reasons for studying the productivity of single-grip harvester cutting are various. The most typical task is to investigate the main factors affecting work productivity and to establish a base for cost calculations and salaries or payments. Researchers, in particular, may today have other reasons to conduct productivity studies; accurate models may be utilized in different kinds of simulations that aim to find new, more efficient work methods, optimize complete operations or develop more efficient machines (Aedo-Ortiz et al. 1997, Wang and Greene 1999). Typically, productivity has been studied after the factors affecting it have changed and the previous models are no longer valid: new harvester concepts, new cutting methods, new cutting directives or some other change compared to the previous situation. In addition, ways to increase productivity and profitability are always in the minds of harvester contractors. By increasing productivity the unit costs of cutting will decrease, which will reciprocally increase profitability in addition to the contractor's income.

Typical work study methods for studying the harvester work have been time study and method study, in combination with measures of the production. In order to study the productivity of harvester work, time studies are used to determine the input-element of productivity to study factors affecting productivity or to develop work methods eliminating ineffective time (Harstela 1991). A time study is usually done either as a comparative study, a correlation study or a combination of the two (Eliasson 1998). The objective of comparative studies is to compare two or more machines, work methods, etc., while the objective of the correlation or relationship study is to describe the relationship between performance and the factors influencing the work (Samset 1990, Bergstrand 1991). Time studies can be carried out using continuous time study methods such as continuous or repetitive timing or indirect work sampling (Forest work… 1978, Samset 1990, Harstela 1991). The work sampling technique gives only an approximation of the results obtained by the continuous time study methods, but it has the advantage that longer periods and even multiple processes can be studied at the same time with the same costs (Miyata et al. 1981). Correspondingly, method study can be seen as a rationalizing procedure aiming to develop work systems according to the targets set by the investigator and producing knowledge about the work under examination (Harstela 1991). Work measurement is included in the method study investigating the ineffective time associated with the work (ILO 1981). Typically, the time study is the work measurement method in the harvester work studies.

In general, the productivity of harvester work is based on three main factors: forest, harvester and operator (Figure 1). All of them are essential in determining productivity and are interconnected during the work, for example, when the volumes of the stems increases in the stand, the harvester is loaded more and the operator needs to think and steer the harvester head differently to enable fluent and thus productive work movements. In the following sections, these three main factors are discussed.
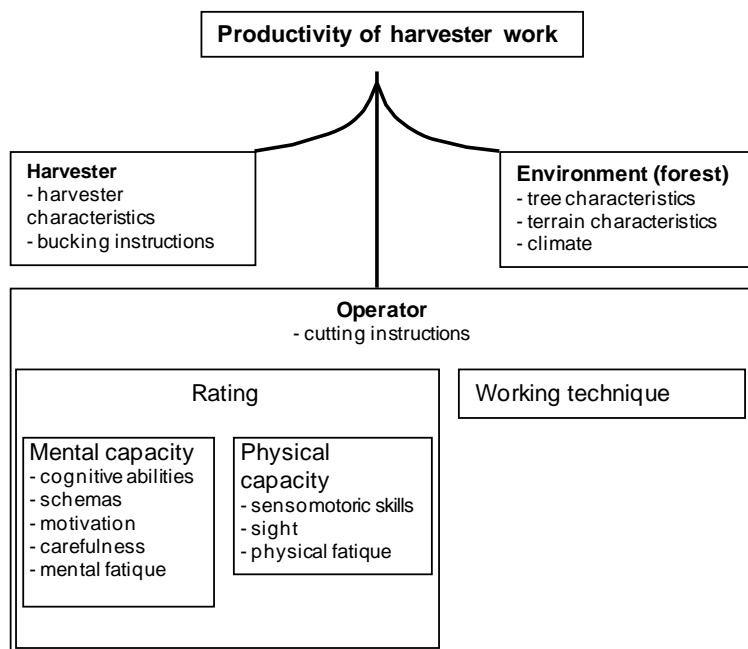
Figure 1. Main factors influencing cutting productivity in harvester work.

1.2.2 Environment

Tree size is the most determining variable of the environment (forest) characteristics concerning harvester productivity: the increasing tree size increases productivity, which has been proven in many studies in the Nordic countries (Brunberg et al. 1989, Kuitto et al. 1994, Brunberg 1991, 1997, Lageson 1997, Eliasson 1998, Sirén 1998, Glöde 1999, Hånell et al. 2000, Ryynänen and Rönkkö 2001, Kärhä et al. 2004, Nurminen et al. 2006) and also in Northern America (Tufts and Brinker 1993, Kellog and Bettinger 1994, McNeel and Rutherford 1994, Landford and Stokes 1995, 1996, Tufts 1997). Modern harvesters are so effective that it takes only slightly more time to process a large tree compared to a small sized tree. This inevitably leads to an increase in productivity as stem size increases. However, the relationship is not linear. After a certain stem size, optimal for the machine in question, the productivity starts to decrease (McNeel and Rutherford 1994, Ryynänen and Rönkkö 2001, Kärhä et al. 2004). At this point the trees start to be too large for the machine. In addition to tree size, the productivity of harvesters has been noticed to increase with enhanced harvesting intensity or the number of trees removed in clear cutting (e.g. Kuitto et al. 1994, Brunberg 1997, Eliasson 1998, Sirén 1998), but also in thinnings (Sirén 1998) and in shelterwood cutting (Hånell et al. 2000). Other factors than the properties of standing trees that affect the productivity are terrain characteristics: slope (Stampfer and Steinmüller 2001), surface structure and ground strength. Climate conditions may also influence cutting work: lightning, precipitation (water, snow), temperature and the amount of snow (Uusitalo 2004).

Tree size is also a determining factor when selecting a suitable harvester model for cutting. Harvesters are classified and built according to the characteristics of the cutting areas. Smaller harvesters are meant for stands where the tree size is small (e.g. thinning) and while large harvesters are suitable for stands with large trees (e.g. clear cutting). A suitable harvester in appropriate conditions also often leads to the best economical result.

Thinning and clear cutting situations are rather different although similar trees are felled and processed in both kinds of stands. In thinning, the number of factors to be taken into account, on which the harvester operator's decisions are based, is considerably larger, compared to clear cutting, where work is freer. The most notable difference, in addition to tree size, is that in thinning many trees are left standing in contrast to clear cutting where all the trees are felled. Standing trees have a limiting effect on the harvester head's free movement, and the smaller the trees are the less free space there is to move the harvester head. In clear cutting, tree selection for felling happens on the basis of tree location in relation to other standing trees. However, in thinning, the tree selection is influenced by density of stems and crowns, tree species, sign of root rot and damage, height, diameter, location of the tree, bend, placement, and form of branches as well as the position of the machine regarding trees, gaps and obstacles (Gellerstedt 2002). In addition, the remaining trees should not be damaged and other silvicultural guidelines (such as biodiversity) should be taken into account. Harvester operators need to also control the width of the strip road keeping it between 4 – 4.5 meters, with a gap of 20 meters between each one (Hyvän metsänhoidon…). Therefore, the listed reasons influence the productivity in thinning and make the work more complex compared to clear cutting.

The basic problem of thinning cutting: moving of harvester head in the environment of the remaining trees has been studied using simulation (Eliasson 1999, Wang and LeDoux 2003, Wang et al. 2005). In the studies the limiting effect of remaining trees has been modeled. However, the modeling do not take account the issue of how much the distance of a tree from the boom base influence the harvester head movement. It can be assumed that a tree located closer to the boom base limits more the harvester head movement on the

working sector than a tree located further from the boom base. In thinning the trees at the side of the strip road are located nearest the harvester head and boom so it is assumable that those trees influence the harvester head movement and harvester work more than the trees on the stand side.

1.2.3 Harvester development and work

In the end of the 1970s the technology of CTL method single-grip harvesters developed rapidly. At that time the harvester's main structure was developed, which is still the general form of the machines used today. In the early stages of harvester development the technical improvements in machine construction considerably increased productivity. The harvester itself had a bigger influence on the productivity than the operator as a machine user. Nowadays, all harvesters of the same size are almost as productive as each other in similar conditions. Reasons for this are that harvesters are partially composed of parts from the same suppliers and that a certain kind of machine construction has been seen as the most practicable among harvester manufacturers and operators. Nevertheless, a higher level of productivity is being sought by the harvester manufacturers. Currently, increasing productivity through technical solutions is an expensive way, and the reduction in the importance of the brand of the harvester places more significance on the skills of the harvester operators (Figure 2). Therefore, the focus has been directed to skilful operators and operator training, because the harvester operator has been found to have a crucial influence on the productivity (Sirén 1998, Sirén and Tanttu 2001, Kariniemi 2006). Even more than 40% differences in productivity have been observed among operators in similar conditions (Ryynänen and Rönkkö 2001).
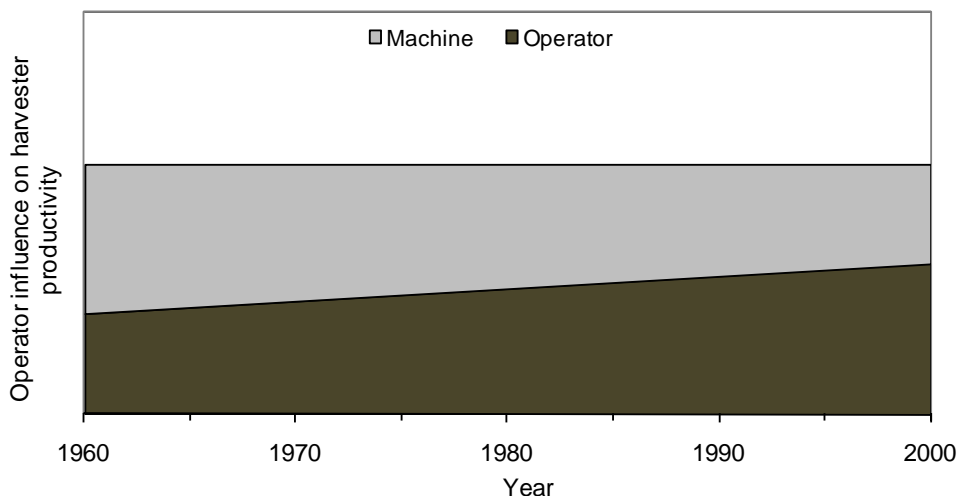
Figure 2. The change of influence of harvester operator on the productivity of harvester work.

Harvester work can be divided into six work phases: moving, steering the harvester head to the tree, felling of tree, processing (delimbing and crosscutting), boom-in and non-productive time (Nurminen et al. 2006). Since the end of the 1970s the demands on the operators have changed and increased, and the harvesters have been developed in an attempt to increase automation in machine functions in different work phases (Tynkkynen 2001a). However, only the processing work phase of the work phases can be performed automatically today, if the quality of the stem is good when the operator does not need to change the cross-cutting points selected automatically by the harvester. To perform the other work phases the harvester operator is needed. For this reason, the operator is still an irreplaceable part of harvester work and design.

During the last decade, diesel engines, hydraulics, feeding motors, delimbing knives, sawing motors, measuring and bucking computers have been developed in harvesters (Nurminen et al. 2006). This has increased the productivity levels, especially in clear cuttings. On the other hand, the number of wood assortments cut in one stand has risen during the decades, which have also been found to influence productivity (Brunberg and Arlinger 2001, Nurminen et al. 2006). However, the productivity of thinning cuttings has not increased. As described in chapter 1.2.2, this can be explained by the more complex combination of different factors influencing the cutting work when the direct technical improvements of the harvester are not so meaningful. For this reason, the role of the operator is emphasized in thinning when the stem size explains only a part of the efficiency and a lot of planning and decisions, simultaneously with harvester steering operations, are included.

A harvester combined with a forwarder constitutes the dominant harvesting chain in Finland. Stem size also influences the productivity of the forwarder, but not so extensively as the harvester (McNeel and Rutherford 1994). Especially in first thinning, the harvester's productivity is considerably smaller than the forwarder, which should be taken into account regarding machine scheduling (Tufts 1997). The piling of logs has been found to influence the productivity of the harvester-forwarder chain, therefore, being one way to balance this chain (Gullberg 1997, Väätäinen et al. 2005). When the logs are piled more in cutting, the harvester productivity decreases, whereas, the forwarder productivity increases since the number of loadings decreases.

In harvester work, the payment of the performed cutting work for the contractor is typically based on the produced cubic meters. In cutting, the only work phase producing cubic meters is processing; the other work phases are necessary but they do not produce cubic meters directly. For this reason, the time spent on those other work phases should be minimized and the processing time maximized.

1.2.4 Operator: rating and working technique

Harvester operator has been stated to be the most important factor of productivity (Purfürst and Erler 2006). The influence of the operator on the productivity can be divided into rating and working technique (see Figure 1). Rating is generally defined as "the assessment of the worker's rate of working relative to the observer's concept of the rate corresponding to standard pace" (ILO 1981). In practice, in harvester work, rating would mean perceivable speed that is visible in work functions. In other words, how fast the harvester and harvester head are moved. Working pace concept is also used (ILO 1981). Rating is based on the physical and mental capacities of the operator. Today, the main physical factors causing strain are whole-body vibration and static muscle load causing pain in the neck, shoulder and lower-back area (Axelsson and Pontén 1990, Hanson 1990, Sherwin et al. 2004). The

senses, especially sight, are exposed to a large amount of information from the surroundings (Vuorinen 1978, Harstela 1979) as well as from the harvester monitor (Forsberg 2003). Fatigue has been also observed to impact on the operator's alertness and productivity (Nicholls et al. 2004).

Instead of physical workload, a modern harvester operator is increasingly exposed to a high mental load. Significant information flow from the surroundings (trees, ground obstacles, etc.), with repeated fast decision-making situations in a dynamic working environment with contradictory demands, places mental strain and stress on the operators (Tynkkynen 2001a, 2001b, Berger 2003, Ranta et al. 2004). In cognitive work, memory, learning, thinking, perception, vigilance, creativity and problem solving abilities are put under pressure. Therefore, the cognitive work results in a large mental strain on the operator, which has been found to be the biggest limiting factor in the processing of information and thus also influence the productivity of harvester work (Nåbo 1990, Gellerstedt 1993, 1997).

From the standpoint of control inputs during harvester work, a harvester operator performs, on average, 12 movement series per minute, with each series consisting of more than one movement (Harstela 2005). Gellerstedt (2002) observed that operators made 4 000 control inputs during a machine hour. The number of decisions is much greater than the number of measurable control activities, most of which are automatic (Harstela 2005). Harvester operator's work has been compared also to that of fighter pilots where the same kinds of skills and stressful situations have been observed (Sullmann and Kirk 1998, Harstela 2005).

Another human dimension to productivity are cognitive abilities. They are matters that are inherited at birth, therefore, the possibilities to improve them are rather limited. The cognitive abilities of the harvester operators have been studied variously for decades. However, forwarder operators' abilities have been studied since the 1960s from which a point of contact to harvester work can be found on the basis of similarities in boom work. In a study by Andersson et al. (1968), the variables of technical-mechanical skills, coordination and reactivity explained the forwarder operator's success in work. Lehtonen (1975) concluded that the most important abilities characterizing loading were spatial aptitude, perception and memory. Leskinen and Mikkonen (1981) found that coordination, deduction, stereoscopic vision and both technical and visual aptitude have a significant prediction value in forwarder work. The conclusion from a workshop, which included harvesting specialists and a psychologist, showed that the requirements for the harvester operator were psychomotricity, visual memory, spatial relation, attention, auditory memory, non-verbal intelligence, basic calculation and general intelligence (Parisé 2005).

Gellerstedt (1993), Tynkkynen (2001a), Ranta et al. (2004) and Kariniemi (2006) have showed that mental models, schemas, are important in an operator's data processing and, furthermore, schemas are strongly linked to cognitive abilities. Schemas are mental, sketchy, working models in brains of which the most suitable working model for the situation is generated on the basis of previous experiences and reactions (Neisser 1976, Rasmussen 1986). Schemas include only the outline of the action and are completed with details during the progression of action.

Working technique, in other words, how the work is done personally, is the other side of the operator factor regarding productivity. One definition for the term *technique* is "the knowledge and the utilization of the most appropriate and work saving methods" (Otavan… 2002). Numerous definitions exist for the term "work", but one is "meaningful activities involved in gainful employment" (Harstela 1991). Thus the general definition of the working technique includes both methodological and economical parts of the work. In this study, working technique is understood as visible and measurable movement of harvester

and harvester head from one place to another. Movement can be measured in time and distance. Working technique exists both on a working location and on a tree level, because working technique includes both moving the harvester and harvester head. In other words, it includes working cycles of single trees, selection of working location and processing order of trees.

In harvester work, planning of work exists in different phases of work and on different decision making levels. It has been found that the harvester operators make decisions on a stand, a working location and a single tree levels (Ranta et al. 2004, Kariniemi 2006). As a consequence, the concept working technique can be understood in different ways on different levels. The concept "working technique in forest machine work" is normally associated with the stand level where most of the productivity studies are also done. Typically, the stand level layout has been used to present progress of the moving and cutting work phases of harvester. In the stand level studies, the aim has usually been to compare working methods, for example, working methods of small size harvesters in selection thinning (Kärhä et al. 2004) or a comparison of selection thinning and row thinning in row plantation (Suadicani 2004). Instead, in simulation studies of thinning cutting, time consumption and the harvester head's reach to a single tree, limited by remaining trees in a working sector of a boom, has been contemplated and modelled (Eliasson 1999, Wang & LeDoux 2003, Wang et al. 2005). However, the viewpoint of these studies has still been on the stand level productivity and, for example, the influence of changing the steering method of the harvester head, concerning one tree, due to different working techniques has not been studied on a single tree level. The moving distances of the harvester head in different working phases has been estimated to some extent (Sirén 1998), however, comparative studies of different kinds of methods of moving the harvester head or selection orders of removable trees in a working location have not been made. This would be important since Ranta et al. (2004) has stated that the operators' "play" the trees in a working location as a chess player plays pawns on a chessboard, which means that some techniques are more "productive" than others.

The last point is strongly related to tacit knowledge and learning. Tacit knowledge means know-how, which is obtained through work experience existing as schemas and attitudes in practice. Tacit knowledge is difficult to express verbally or formally (Nonaka and Takeuchi 1995). Professional harvester operators have a lot of tacit knowledge since smooth harvester steering and high productivity are reached through actual working and learning in practice. According to Ranta et al. (2004) harvester operators' tacit knowledge is related to perception, planning of work, anticipating, evaluation of activity on different decision making levels and proper boom handling skills. Therefore, it would be important to transfer the tacit knowledge of experienced harvester operators to the training of beginners, when learning-by-doing would decrease and the productivity level of graduated operators would be higher.

In addition, harvester simulators are frequently used today in the operator training in harvester operator schools. Furthermore, the number of training hours has been increasing all the time. The positive effects of harvester simulators in a form of higher productivity and increased self-confidence to operate with the harvester have been reported in many studies (Freedman 1998, Wiklund 1999, Yates 2000). In a harvester simulator the same cutting situation can be repeated when more exact comparison of different working techniques is enabled. For these reasons, teaching on the simulators is, nowadays, a fixed part of the operator training. However, the working environment of the virtual simulator is always more or less a simplified version of reality and thus it can create incorrect work models for the trainee if the trainee is not aware of the reality differences (Juola 2001). For

this reason it would be reasonable to present the differences already in the beginning of simulator training.

Working technique is an operator-specific feature of the harvester work also including tacit knowledge to some extent (see Figure 1). People are individuals, for which they all have their own, sometimes self-learnt, habits to do things (Saariluoma 1990). Working technique habits also influence the harvester work to some extent, but the common features of working techniques are rather similar between operators due to the fact that rather similar kinds of machines are used in rather similar types of conditions. However, some working techniques diminish more unnecessary work movements than some others being, therefore, more productive. As mentioned earlier, there are three ways to reach higher levels of productivity (m^3/h): increasing the production while the time remains the same or lowering the time while the production remains the same or changing both production and time. The first way, production increase, may require a new mechanical invention as well as improvements in machine construction, in other words, a significant amount of engineering work. This is often an expensive way leading to higher machine purchasing costs and thus the overall benefits of the productivity increment are low. The third way, changing both factors in the equation, may require a new machine that needs a totally different working technique. The second way is to change the divisor in the productivity equation: when the time spent for each cubic meter is smaller productivity will increase. In harvester work this means that the work phases are performed in a shorter time. This focuses mainly on the harvester operator with two main factors influencing the cubic meter time: rating and working technique. Rating can be improved by increasing working speed while the working technique can be improved by correcting imperfections of the harvester head movements. In this study the focus is on working technique, which is measurable and more concrete to improve than rating, which is highly dependent on the operator's cognitive abilities and sensomotoric skills in the present-day harvester work.

1.3 Objectives of the research

The principal objective of this research was to discover and describe a productive working technique for harvester work in first thinning and to improve harvester operator training by pointing out the problems of harvester simulators and determining the important cognitive abilities needed in harvester work.

The specific objectives of the sub-studies were:
1) to investigate the effect of different working techniques of six professional operators on the work performance in first thinnings. The differences between the operators' working techniques were analyzed in detail for each harvester work phase and the motives and effects of the techniques employed are presented. Also, the general features of the different working techniques are described (Study I),
2) to compare harvester work in the forest with simulator environment at each phase of work, and to describe how and where the operators' working technique may change in the simulator environment compared to the real forest. Special characteristics and differences in the productivity of the simulator are also presented on the basis of resemblance to reality (Study II),
3) to determine the influence of edge trees on the positioning of modern single-grip harvester in first commercial thinning. Other reasons (such as the harvester operator's field of vision and cab – boom base configuration) for a specific machine position in the strip road are also discussed from the working technique point of view (Study III) and

4) to discover how professional harvester operators' and operator students' information processing abilities, especially visuospatial cognitive abilities, explain the productivity of harvester work and skilful harvester operating. This study also characterized a productive harvester operator's mental abilities (Study IV).

All the study results can be considered under the development work of harvester operator education, producing more qualified operators since the material for the study was collected mainly in ProForSim -project that aimed at better education of young harvester operator students. The results also provide features of productive operators for operator selection. Studies I and III are related, focusing strictly on the working technique. Study II produces knowledge for the harvester simulator training. The Study IV concentrates on the mental side of the harvester work. On the basis of this whole research factors describing harvester operators working technique can be presented and the importance of the cognitive abilities justified.

2 MATERIAL AND METHODS

2.1 Characteristics and significance of a harvester operators' working technique in thinnings (Study I)

2.1.1 Study stands and experiments

The whole research was started by arranging cutting studies in a forest in the fall of 2002. The purpose was to collect cutting data of six harvester operators with time study and work technique observation methods joined with automatic PlusCan recording. Harvester work was studied in two different kinds of Scots pine (*Pinus sylvestris*) dominated thinning stands and one spruce (*Picea abies*) clear cutting stand located in Northern-Carelia, in Eastern-Finland (Table 1). The overall aim of the stand selection was to create similar conditions for all the operators when the number of factors affecting the work would be minimal and the influence of the operator on work performance would be the main focus. For this reason, thinnings and clear cutting stands were selected so that tree stand variation within the stands was minimized and circumstances were very similar for all harvester operators. Both thinning stands were thinned according to the standard thinning instructions from basal areas of 22.0 and 19.8 m^2/ha to 14.0 and 13.2 m^2/ha. The initial number of stems in stands a and b was 1232 and 1071 stems/hectare, respectively. The total mean stem volume of the commercial part of the removed stems was 82 dm^3 in thinning.

In all stands each operator cut three experiment areas during one day. The time of the experiment was set to be 60 minutes of effective work in stand a, and 45 minutes in stands b and c. The operators were allowed to freely choose the location of the strip road in the thinning as they do in their normal work. Trees were not marked prior to harvest, so the harvester operator was responsible for selecting the stems to be removed. There was at least a 30 minute break between the experiments.

Table 1. Characteristics of the study stands.

Environment	Trees/ha, merchantable / all (before cutting)	Trees/ha, merchantable / all (after cutting)	Average height, m	Average dbh, cm	Merchantable trees, total
Thinnings					
a	1232 / 1544	643 / 813	14.6	12.7	1913
b	1071 / 1587	630 / 985	14.4	13.2	1385
Clear cutting					
c	473	-	19.4	22.1	705

Within the stands the experiment areas were chosen so that the terrain variation was minimal and thus only had a slight impact on the operators' decision making in the experiments. Areas of the stand, which include slopes or swamps, were not included. The ground of the experiment areas was mostly flat and free from obstacles that could restrict normal movement of the harvester. The ground had a snow cover of 20cm during the experiments in thinning with snow falling from the trees, which slightly restricted visibility in the tree grabbing and felling phases. In the clear cutting stand, the ground had 30cm snow cover and the falling snow from the trees covered visibility for many seconds (5-10 sec) in the tree grabbing and felling phases, if the operator grabbed the tree too strongly.

2.1.2 Operators and harvester

Six professional harvester operators (A-F) were selected from various logging contractors for the study cuttings. They had work experience of single-grip harvesters from 2 to 10 years and most of them had experience of operating forwarders as well. The operators' ages ranged from 26 to 52 years at the time of the study. Operator E had previously been a logger. At the study time, most of the operators' work sites were focused on thinning stands. The operators had experience of many harvester models but the demands set for the operators were that they were familiar with Timberjack harvesters and the Timbermatic 300 measurement and control system due to study arrangements. A new Timberjack's harvester that was recently bought by the harvester operator school of Valtimo was used in the study cuttings.

All the operators operated with the same single-grip timber harvester as the research arrangements for the experiment cuttings required (Figure 3). The harvester was medium-sized, common in Finnish conditions and could be used both for thinning and clear cutting stands. The harvester was fitted with a parallel motion knuckle boom with a slewing angle of 220° and reach with the harvester head of 10m. The tires were mounted with tracks on the front and chains on the back.

Figure 3. Study harvester Timberjack 1070 C with Timberjack H754 harvester head. Photo by Kari Väätäinen.

Before the first experiment in the stand, the operators familiarized themselves with the harvester, boom and other properties of the study machine for about an hour. The operators were allowed to adjust the boom movements and speeds as they liked in order to achieve the same kinds of motion speeds they used when using their own harvester. Bucking instruction file (APT) was the same for all operators but the operators were allowed to set some desired log lengths into certain length buttons, for example, long pulp wood. The overall aim of the harvesting session in the experiment was that the operators could achieve the same kind of work performance as they do in their everyday work.

2.1.3 Data collection methods

The work-study consisted of two separate studies that were carried out simultaneously by two researchers: a time study and a work technique observation. The time study was made using the basic work phase observation method, where the work phases were divided into 5 main stages: moving, positioning-to-cut, felling, processing (delimbing and crosscutting), and non-productive time (Table 2). In this study, some work phases were divided into even more detailed units. Moving was observed when the harvester tracks started moving and ended when the harvester stopped moving to perform some other task. The moving was divided into driving forward and reversing. Positioning-to-cut time started when the boom started to swing toward a tree and ended when the harvester head rested on a tree. The felling work phase started when the felling cut began and ended when the feeding and crosscutting work phase was launched. Felling was divided into two categories: normal felling and felling with moving of stem over 3 meters. Dragging of stem on the ground was measured in clear cutting. Processing consisted of delimbing and crosscutting. The processing phase ended when the operator started to do the next work phase. In processing, trees with two or more tops were divided into time units by each top section of the stem. Non-productive time consisted of clearing, steering the boom front, piling of logs, moving tops and branches and short delays, which were caused by the operator. Steering the boom front occurred when the operator steered the harvester head to the front of the machine before the moving phase. Total effective working time included all previous listed work phases and all delays and breakdowns caused by machine or its data system were excluded.

Table 2. Time study and observation of working technique divided into detailed units.

Time study	Observation of work technique
1. Moving	Observations per tree
- driving forward and reversing	1. Pick-up side (left, right, front)
2. Positioning-to-cut	2. Tree species
3. Felling	3. Pick-up direction; front, obliquely, vertically
- felling (moving of a stem less than 3 meters)	4. Distance of the removed tree, m
- felling with moving of a stem over 3 meters	5. Felling direction
- dragging of stem on the ground	6. Processing location related to harvester
4. Processing	7. Distance to the processing location, m
- following of the stem with the harvester head	
5. Non-productive time	Observations per moving
- Clearing	8. Starting time in working location
- Steering the boom front	9. Moving distance between working locations, m
- Piling logs	
- Moving tops and branches	10. Distance to nearest trees on the strip road after moving, m
- Delays	

In the observation of working technique, distances of the removed trees, processing places, boom directions and machine movements based on visual estimates, were all observed and noted by the researcher during the experiment cuttings. All distances were estimated at a vertical angle from the middle line of the strip road except moving distance and the distance of the wheels to the nearest trees on the strip road, which were estimated along the strip road. Moving distances smaller than 0.5 meters were not marked down. In this case tree pick-up angle was divided into three categories: front (means strip road), obliquely from side (0-70°, does not include strip road) and vertically from side (70-110°) (Figure 4a). Felling direction included four classes: away from the strip road, towards the strip road, backwards and forwards parallel to the strip road (Figure 4b). If the harvester operator cleared small trees before a merchandised tree, the number of clearings was marked down. The processing place was divided mainly into two cases: processing besides the strip road and processing on the stand side. In the first case branches and top were left on the strip road and logs were fed away from the strip road. In the second case crosscutting was done on the stand side and feeding direction of the logs was toward the strip road. Top and branches were left on the stand side. Distance to the processing place from the middle line of the strip road was also estimated.
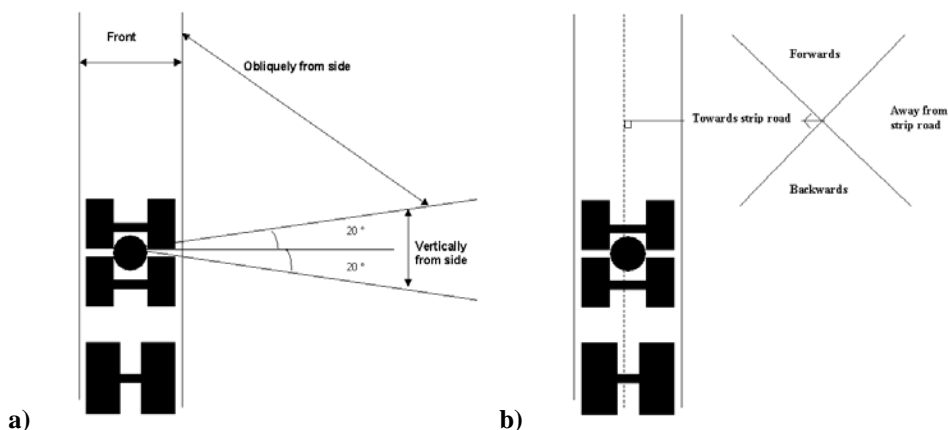
Figure 4. Pick-up angles (**a**) and felling directions (**b**).

The automatic data logger PlusCan (manufactured by Plustech Ltd) was also attached to the harvester, which monitored CAN-buses of the harvester. The device collected detailed process data of the work phases and information about processed stems. In this study only the stem volumes collected by this data logger were used.

The data of the work technique was recorded using a Psion hand held computer. While a Rufco hand held computer was used to record data for the time study. Work technique observations were joined by stopwatch study time units for each handled tree as a large matrix after data collection first in MS Excel software and continuing the analysis with SPSS statistical software. Also the volumes of the stems were added.

In the results selected values indicating the productivity of an operator were presented to show the productivity differences among operators and distinguish a productive harvester operator. Productivity values were calculated separately for both stands. Because of the imperceptible differences in the operator's working techniques in both stands, the observed values of working techniques were joined and analyzed together.

2.2 Comparison of harvester work in forest and simulator environment (Study II)

In Study II, the aim was to make the same kind of cutting situation and data collection as in Study I except the working environment would be a harvester simulator. This would enable a better comparison of work performances between the environments. Therefore, harvester work was timed and the working technique was observed in a similar manner as in Study I. The work phase division in time study, work technique observation, PlusCan, data collectors and data collection devises were the same as in the forest study. In addition, the harvester operators were the same.

The harvester work was simulated by using a Timberjack harvester simulator, which was equipped with actual harvester control levers, including a complete Timbermatic 300 system (Figure 5). The hardware elements such as operator chair, controls, and onboard computer were taken from a real machine, and the software was programmed accordingly.

Figure 5. Timberjack harvester simulator. Photo by Plustech Oy.

In the simulator, all the operators cut the same thinning stand twice and the same clear cutting stand once. The harvester simulator stands were designed to correspond, both numerically and visually, with the stands cut in the real forest in Study I (Table 3). Each simulator experiment lasted 40 minutes. Before the first experiment the operators were allowed to practice with the harvester simulator, because some of the operators had never used a simulator.

On the harvester simulator, a generated stand consisted of 12.5 x 12.5 m squares. Trees were generated on the squares on the basis of tree height and species, and the number of trees growing per hectare. The tree height varied a maximum of one meter around the given height. Tree diameter at breast height, 1.3 m (dbh), was calculated on the basis of tree height. Trees were randomly placed on the squares, and the stand generator created 5 different kinds of squares and utilized those randomly to fill the given stand area. In this study, the simulator stands were generated on the basis of portions of tree species per hectare and the average height of the tree species.

The data of the simulator thinnings was analyzed in one process, because no differences were observed in operators' functions between the two thinning times. In data analysis statistical methods were used to describe the differences between the work performances on the simulator and real forest environment. To describe the differences between the environments in separate work phases, arithmetic averages were calculated. The Wilcoxon Signed-Rank 2-tailed test verified whether the between-environment averages differed from one another statistically significantly in each work phase (Ranta et al. 1999). If the significance (p-value) was less than 5%, the difference was statistically significant. The use of a non-parametric test was based on the fact that the averages were not normally distributed. In addition, the number of averages in the test was small.

Table 3. Stand characteristics of the thinning stands and the clear cutting stands on the simulator. Average tree height and diameter are calculated on the basis of removed trees.

Environment	Trees/ha, merchantable	Average height, m	Average dbh, cm	Merchantable trees, totally
Thinning	1 808	11.6	18.7	797
Clear cutting	464	18.7	29.5	334

2.3 Effect of edge trees on harvester positioning in thinning (Study III)

2.3.1 Helmet camera video taping

The aim of Study III was to determine the influence of edge trees on the positioning of the modern single-grip harvester in first commercial thinning. The data used in Study III consisted of observations collected visually from the videotapes. The reason for using video material in the data collection based on the fact that other kind of data collection would have disturbed the operator's normal work performance too much. Videotaping was carried out in the third experiment area of each study stand (same stands as in Study I) but in this study the video material from stand b was used. In that experiment all the operators were operating in a very similar location in the stand. The operators' work was videotaped using a digital video camera recording from the operators' point of view. A small digital video camera was attached to the helmet on the operator's head (Figure 6). As with typical harvesting work the operator is required to observe the surroundings constantly, which enabled the recording of felled trees, remaining trees and bunches of logs. The operators also had modified eye shields on their heads, which restricted the field of vision so that the operators had to turn their heads, and thus the camera, in the direction of view.

Figure 6. Helmet camera used in the study and modified eye shields. Photo by Heikki Ovaskainen.

2.3.2 Definitions

To enable data collection, new definitions must be given for the trees and the areas in the surrounding the harvester (Figure 7). In thinning, the cutting site can be divided generally into two parts: the strip road and the stand side. The outer zone of the stand to be thinned next to the strip road was known as the stand side. Furthermore, one part of the stand side belongs to the edge zone, which reaches about 3m from the line of the edge trees to the stand side (Isomäki 1994). The edge trees are located along the side of the strip road, on average 2.25m from the strip road centre. An edge tree is generally defined as a visually individualized tree that obviously restricts the movement of the harvester in the strip road

zone (Isomäki 1994). The average width of the strip road is typically 4.5m (Väätäinen et al. 2005).

When the harvester and the edge trees were in the same figure (Figure 8) the edge trees around the harvester were defined as rear and front edge trees. The boom base defined the position of the harvester in relation to the edge trees. Once the boom base had passed the edge trees, they were considered as rear edge trees. Correspondingly, the edge trees in front of the boom base were considered as front edge trees. A sequence of edge trees is the distance between two consecutive edge trees along the side of the strip road. Two adjacent edge trees at opposite sides of the strip road formed a line of edge trees.
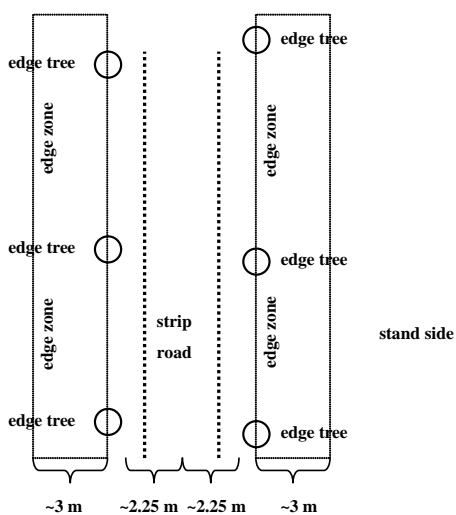
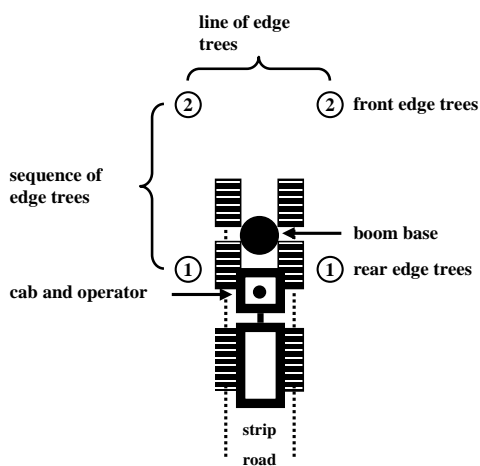**Figure 7.** The concepts and average distances of strip road surroundings.

Figure 8. Harvester surroundings concepts.

2.3.3 Data collection and analysis

When observing distances, using the video recordings, almost in all estimates the boom base was the center point from which the distances were estimated. Felled trees were estimated in relation to the boom base, for example (Figure 9a). The location of the felled tree was calculated from the ocular boom angle and distance estimate from the videotape. The angle between boom and strip road was estimated to the nearest 5°. An angle value of 0° meant that the tree was felled from the strip road in front of the harvester and if the tree was taken at right angles from the stand side, the angle of the boom and the strip road was accordingly 90°. The distance between the location of the felled tree and the boom base was estimated to the nearest 0.5m. At the tree grabbing moment, the position and the length of the boom helped to make the estimation of the boom angle and tree distance more accurate. Once a stem was processed, the location of the bunch of logs was estimated similarly to the location of the felled tree (Figure 9b). The direction angle of the logs in the bunch was also estimated in relation to the strip road.

In addition to felled tree and bunch estimates, the locations of the rear and front edge trees were estimated visually for each felled tree. The distance between the boom base and edge tree was estimated in a longitudinal direction on the strip road to an accuracy of one decimeter. The edge trees were generally observed from that side of the strip road from which a tree was felled because the harvester is positioned according to edge trees of the felling side. If the tree was felled from the strip road, the edge trees were observed from the side where the operator processed the stem. The average locations of the rear and front edge trees were calculated for both sides of the strip road. The 95% confidence intervals were constructed to describe the variation in edge tree location in a longitudinal direction in relation to the boom base. Furthermore, the distance between the harvester tire track and the rear edge tree was also estimated. The average location of the edge tree could then be calculated when the width of the harvester and the distance of the edge tree from the side of the tire track were known.

The videotapes were watched many times in slow-motion and paused when necessary. This method enabled observation of rear and front edge trees for each felled tree. One person did the data collection from the videotapes in a laboratory. The length of the entire video material from six operators was 270 minutes, which included 487 felled and processed trees.

The distance estimates of the rear edge trees from both sides of the strip road were analyzed in one process, assuming that the side of the stand does not affect the harvester positioning in relation to the edge trees. The Kruskal-Wallis test (K-W) was applied to determine whether the boom base and rear edge tree distances differed between operators. The test does not assume the normality of the distribution. The null-hypothesis, that the distances do not differ between the operators, was rejected if the p-value is smaller than the set significance level (5%).
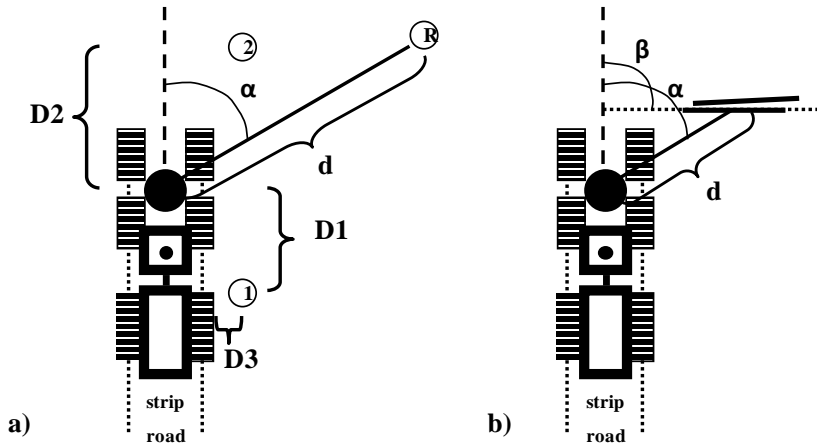
Figure 9 a) Distance and angle estimates for the felled trees. In the figure R = felled tree, 1 = rear edge tree, 2 = front edge tree, α = angle between the strip road and boom at tree grab moment, d = distance from the boom base to the felled tree, D1 = distance between the boom base and the rear edge tree, D2 = distance between the boom base and the front edge tree and D3 = distance between the rear tire track and the rear edge tree. **b)** Distance and angle estimates for the bunch of logs; α = angle between the strip road and middle point of the bunch, d = distance from the boom base to the middle point of the bunch and β = direction of the bunch of logs in relation to the strip road.

Spatial point patterns of felled trees were drawn. The aim of these figures was to see whether there are areas that can be treated or not treated from the most common working location. The centre of the coordinates in the figures was the boom base. In addition to the visual estimation, the point pattern was evaluated using Ripley's K-function (Ripley 1977) to determine whether it is random, clustered or dispersed uniformly. In harvester work, clustering of the felled tree point pattern would mean that many trees are felled from the same locations (sectors) in relation to the harvester. In K(r) analysis, each point (felled tree) acts as the centre of a circle of radius r, and the number of other points within the circle is counted. For n individual points distributed in an area R, the density ($\lambda = n/R$) gives the mean number of points per unit area. The function $\lambda K(r)$ gives the expected number of further points within radius r of an arbitrary point within the area evaluated. If points are randomly distributed, the expected value of $K(r) = \pi r^2$. If $K(r) < \pi r^2$, the point pattern is dispersed uniformly. Correspondingly, if $K(r) > \pi r^2$, the points are clustered. The estimate of edge corrected K(r) for an observed spatial point pattern is

$$\hat{K}(r) = \frac{R}{n^2} \sum_{i \neq j} \sum_{i \neq j} \frac{I_r(u_{ij})}{w_{ij}}, \tag{1}$$

where n is the number of points in the area R; u_{ij} is the distance between points i and j; $I_r(u)$, the counter variable, equals 1 if $u \leq r$ and 0 if $u > r$; w_{ij} is the proportion of the circumference of a circle centered on point i with radius u_{ij}, which lies within R (Bailey and Catrell 1995).

2.4 Visuospatial cognitive abilities in single-grip timber harvester work (Study IV)

The objective of Study IV was to discover how professional harvester operators' and operator students' information processing abilities, especially visuospatial cognitive abilities, explain the productivity of harvester work and skilful harvester operating. Another aim was to characterize a productive harvester operator's mental abilities. For these reasons, the previously mentioned six harvester operators, in addition to 40 operator students (26 second and 14 third year students), were psychologically tested in May 2006. The studied students, aged between 18 and 19, were in the 2nd and 3rd year of vocational harvester operator school of Valtimo. Generally, they had little experience of harvesters, outside of their school training. The psychological tests tested mostly visuospatial abilities, which have been seen to be important in harvester work. Tests AVO-9, WAIS-III and WMS-R were selected for this study to measure visuospatial abilities, long and short-term memory, concentration, attention span, non-verbal deduction and psychomotorics in various ways.

1. AVO-9 is an ability test battery designed to measure the facilities and strengths of a person with a wide range of tasks requiring different abilities (Kykytestistö AVO-9 1995). Sub-tests S2, S3 and V5 of AVO-9 were chosen for this study. The range in the sub-test results is from -3 to 3, norm 0 and standard deviation 1.
- S2: subject must, in their mind, fold together a square that has been folded open. The task requires an ability to observe spatial figures and their relationships.
- S3: subject must divide a figure in two with one straight line so, that a square can be formed from the halves. The task requires an ability to manipulate and re-order spatial forms.
- V5: subject must provide synonyms for a certain word. The task requires verbal comprehension.

2. WAIS-III is an intellectual test designed to measure different aspects of intelligence (Wechsler 1997). In the sub-test the norm is 10 and standard deviation is 3. The tests used for this study were:
- Picture completion (PC): subject must identify the missing part from incomplete, everyday life pictures. The task requires attention, memory, nonverbal deductive abilities, perceptual organization, visual memory and visual organization.
- Block design (BD): subject is presented with red and white blocks, which must be used to construct designs. Task requires spatial analyzing ability and visuomotoric coordination.
- Matrix reasoning (MR): subject must use reasoning and problem solving abilities to complete a design. The task requires analogic reasoning, perception of details and awareness of the surroundings.
- Digit symbol (DS): subject must pair an abstract figure with a number. The task requires speed, short-term memory and visuomotoric abilities.
- Symbol search (SS): subject is shown two abstract figures and must decide whether one of them is in the group of another set of abstract figures. The task requires attention, perceptual organization, speed and short-term memory.
Factors POI and PSI are calculated on the basis of WAIS-III. POI is a factor of organization of perception consisting of PC, BD and MR tests. PSI is a factor of speed of perception consisting of DS and SS tests. In the factors, the norm is 100 and standard deviation is 15.

3. WMS-R is a comprehensive memory test, designed to measure different aspects of memory (Wechsler 1996). For this study all the sub-test were completed. Delayed recall

was performed in an appropriate sub-test. In the sub-tests, the norm is 100 and standard deviation is 15.

VIM
- Figural memory: subject is shown some figures, which he/she must recognize among some other figures.
- Visual paired associates I: subject must connect an abstract figure and a color.
- Visual reproduction I: subject must draw some given pictures.

VEM
- Logical memory I: subject must repeat a short story.
- Verbal paired associates I: subject must remember some paired words.

ATT/C
- Mental control: subject must perform some simple arithmetic.
- Digit span: subject must recite a list of numbers, first forwards and then backwards.
- Visual memory span I: subject must touch some figures in a certain order.

DEL
- Logical memory II: subject must repeat a short story.
- Verbal paired associates II: subject must remember some paired words.
- Visual paired associates II: subject must connect an abstract figure and a color.
- Visual reproduction II: subject must draw some pictures.

GEM = VIM + VEM = A sum of standardized points of sub-tests of VIM and VEM.

The psychological tests were carried out individually on the professional operators while the students were tested as a group. For this reason, the test series for the subjects were different: operators performed all the tests and the students the AVO-9, MR, DS and SS tests. The AVO-9 results could be tested statistically between the operators and students. All the tests were standardized, which enabled performance comparisons with the general population. If the test result was inside the standard deviation of the norm, it was considered as normal performance. Test situations lasted a maximum of three hours, as tests longer than that would have been too tiring for the participants.

3 RESULTS

3.1 Characteristics and significance of a harvester operators' working technique in thinnings (Study I)

As mentioned in the introduction of the productivity differences between operators, large productivity differences were also observed between the studied operators. The operators' relative productivity per effective hour, as a function of stem size, in both thinning stands varied from 40 to 55% in the same stand depending on the stem size (Figure 10). Furthermore, productivity differences increased with increasing stem size. In stand *a* the operators' productivity was between 2 to 18% higher than in stand *b*. However, regardless of the stem size, the most productive operator had almost the same productivity level in both stands. Stand structure affects the productivity, but according to Figure 10, the operator and his work functions have a larger effect on productivity than the stand structure itself.
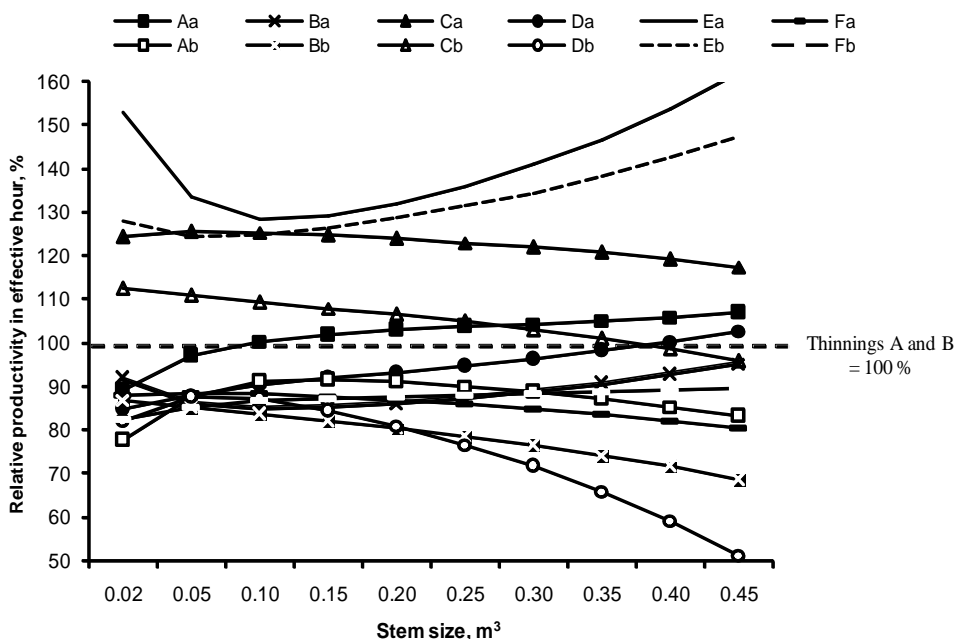

Figure 10. The operators' relative productivity (%) in thinning stands *a* and *b*. Aa = operator A, stand a.

The relational difference in time consumption of each work phase between the operators was the largest in the clearing work phase. Some operators made a very thorough clearing and removed all retarded trees, while the others cleared only what was necessary. Clearing time was separated from the non-productive time.

Total moving time was divided into driving ahead and reversing (Table 4). The most productive operator E reversed only 6.7% of the total moving time; while the least productive operator reversed 18.9%. Therefore, productive operators avoided driving the same distance twice. The operators did not differ significantly in average driving distance between working locations or in number of removed trees in one working location. By using short moving distances the observation and planning of the new working location concentrates on a smaller area. This facilitates the planning of work in a way that a smaller number of factors have to be considered.

The most productive operator had the smallest positioning-to-cut distance, which can be explained by the working technique where as many trees as possible were processed at one stand side (before moving on the other side) (Table 5). Therefore, the operator chose a boom route to stand side between trees so that he could process many removable trees from one side thereby minimizing boom movements. Therefore, the processing of the stem occurred close to the stump. Numerous factors explain the average positioning-to-cut time because the operator has to take into account many things in positioning-to-cut phase. For example, the operator might plan the work during the positioning-to-cut phase or steers the boom carefully to the tree, avoiding damaging the remaining trees, or quickly selects the nearest removable tree to process after the previous one. In the latter case, removing decision is already made before steering the harvester head. The operator should also try to fell and process as many trees as possible from one side before moving to operate on the other side of the strip road.

Table 4. Differences and similarities in the moving work phase.

Operator	Total distance moved, m	Driving ahead/reversing, share-%	Number of working locations	Average driving distance, m	Trees removed in one working location	Speed, meters/minute
A	470	82.5 / 17.5	133	3.5	3.5	12.7
B	387	81.1 / 18.9	118	3.3	3.3	11.3
C	693	86.9 / 13.1	167	4.1	3.8	17.5
D	629	89.3 / 10.7	153	4.1	3.3	17.7
E	693	93.3 / 6.7	192	3.6	3.5	21.5
F	520	86.5 / 13.5	149	3.5	3.3	20.0

Table 5. Total and average positioning-to-cut distance and average positioning-to-cut time.

Operator	Sum of positioning-to-cut distance, m	Average positioning-to-cut distance, m	Average positioning-to-cut time, s
A	1843.10	4.01	9.24
B	1702.00	4.26	9.60
C	2580.80	4.05	7.34
D	2041.80	4.03	10.49
E	2475.80	3.73	7.46
F	2200.90	4.45	10.26

The felling phase was separated into two methods in data collection. The results indicate that unnecessary stem movement in the felling phase should be avoided. Naturally, felling with moving took more time than the pure felling and processing near the stump (Figure 11). The distance of the removed tree did not influence the felling time, but in felling with over 3 meters of movement, the time increased by approximately 2 seconds, when the distance of removed tree from the strip road exceeded 5 meters. Stems, felled with over 3 meter moving, accounted for 35.1% of the total felling amount.

The most productive operator moved 12.5% of the removed trees to the other side of the strip road; the average for all operators was 21.8%. The more productive operators processed trees mainly on the felling side near the stump so that the feeding direction was toward the strip road. For this reason, their average moving distance of the stems was approximately 1.5 meters less than the others. Thereby, they could avoid unnecessary stem movement. If the operator moves the stem over the strip road, it is reasonable to take the next tree from that side. However, in some cases the top of the removed tree got stuck in other standing trees and the best way to dislodge the tree was to move the stem. If the tree got stuck with its top near the strip road, it was moved over the strip road at the same time. In these cases moving speeded up felling. All the operators processed trees mostly on the left side of the strip road. The most productive operators processed almost half of the removed trees on the stand side. As a result the sheltering limb and top mat for the roots of remaining trees was not created on the strip road unless the operator moved the top and branches to the strip road on this purpose. The average distance of the processing place beside the strip road was 2.8 meters and on the stand side 6.0 meters. Different processing places did not influence the average processing times.

The operators' felling directions were divided into different felling sections (Figure 12). Variation in different felling directions diminished when the distance of the removable tree increased from the strip road. Therefore, in large distances of 8 to 10 meters most of the trees were felled away from the strip road. More variation can be seen in felling directions among the operators from the middle of the strip road to three meters.
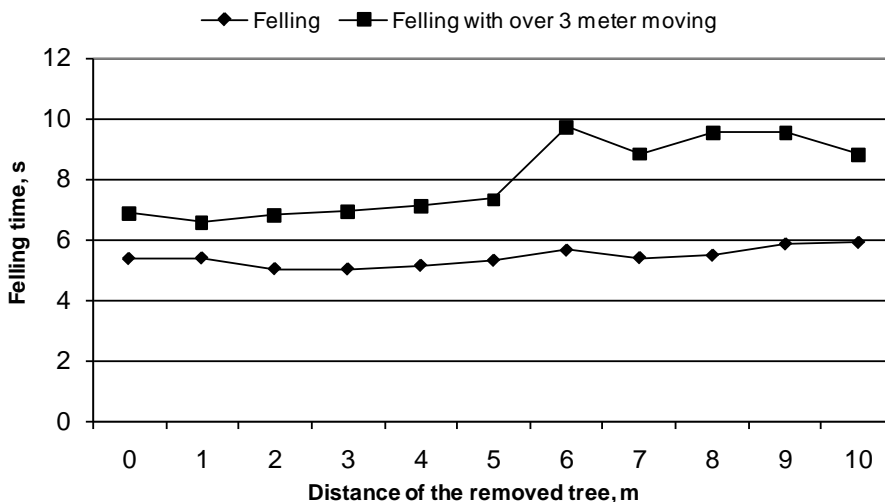

Figure 11. Average felling time for removed trees with different distances from the strip road.
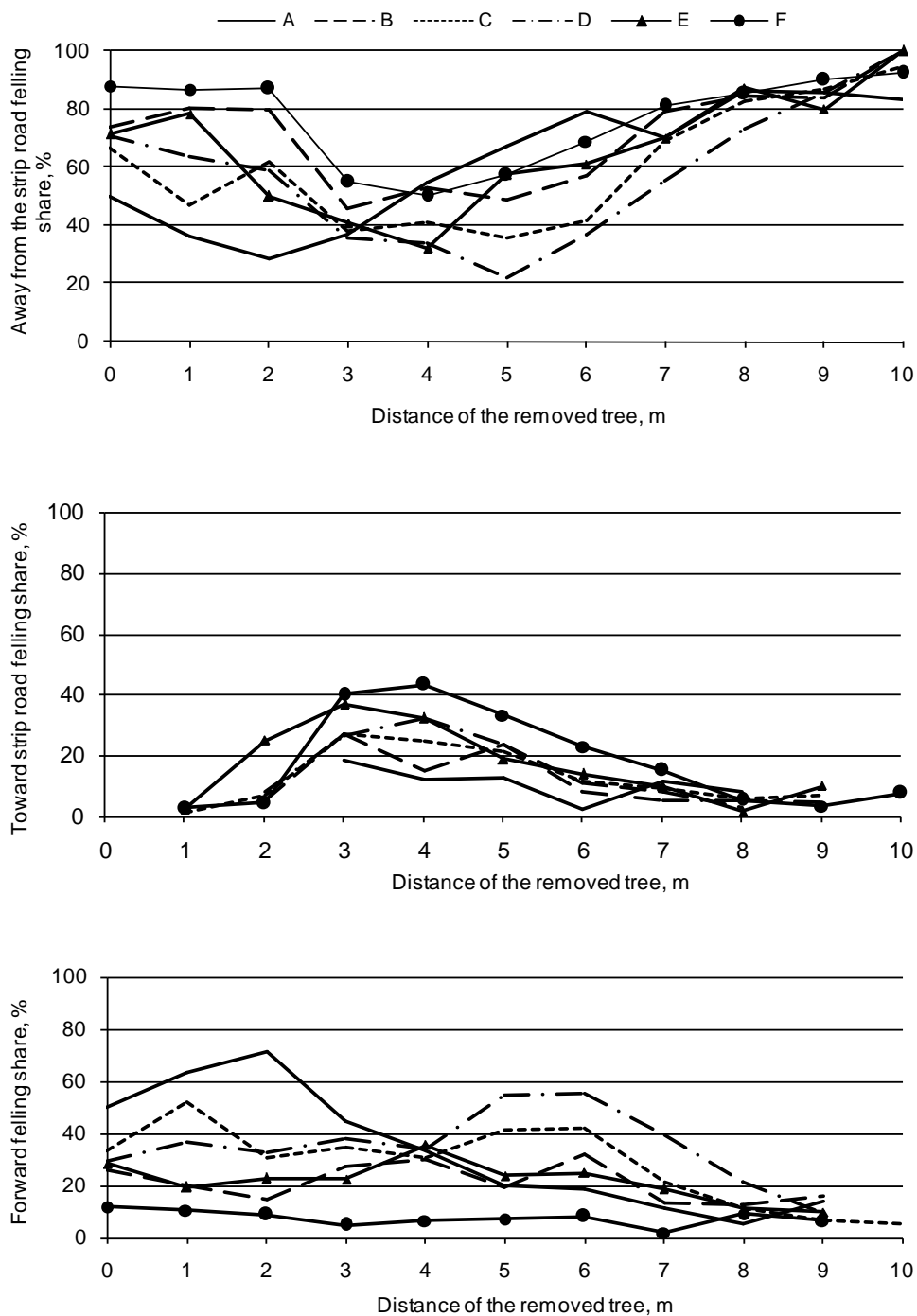
Figure 12. Away from the strip road (top figure), toward the strip road (middle figure) and forwards felling (bottom figure) shares in different distance classes for each operator.

3.2 Comparison of harvester work in forest and simulator environment (Study II)

In the harvester simulator clear cutting, the productivity increased by over 50% from the real environment clear cutting. However, for the thinnings the productivity was very similar in both environments, varying little between the operators. The total time structure as a proportion of effective time was similar in both environments (Figure 13). In both stand types, the largest differences were in positioning-to-cut and processing work phases.

On the simulator, the reversing percentage was bigger than in the forest. This can be explained by the limited visibility to the side. If the operator wanted to "turn his head" and see the sides without steering the harvester head to the side, he had to push a certain button combination and change the view with levers. Therefore, when operators observed removable trees on the side, they usually had to reverse slightly.

In clear cutting, the average positioning-to-cut times were almost the same. However, variation in positioning-to-cut time around each positioning-to-cut distance was large. In other words, at almost the same time an operator might steer and grab a tree within a distance of 1 to 13 m. In the thinnings, positioning-to-cut distance affected the positioning-to-cut time, whereas in the clear cuttings the effect was small; about 1 second in a distance of 13 m (Figure 14). On the simulator, operators had difficulties in discerning the stereoscopic effect of the simulated forest, which caused failed catches and increased the positioning-to-cut time, especially in thinning. In addition, if some part of the harvester head faced a tree, it stopped moving completely. On the simulator, higher tree density also decreased the positioning-to-cut distance.
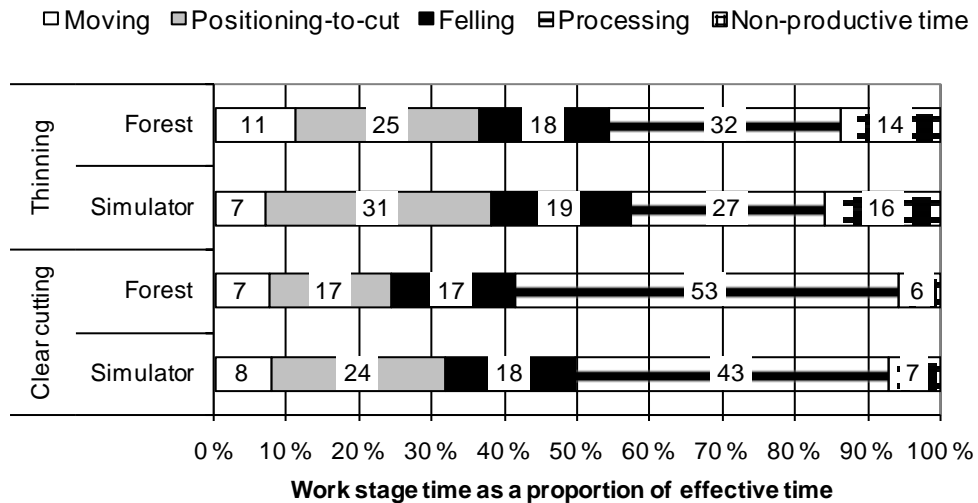
Figure 13. Structure of effective work time divided by main work phases in each environment.
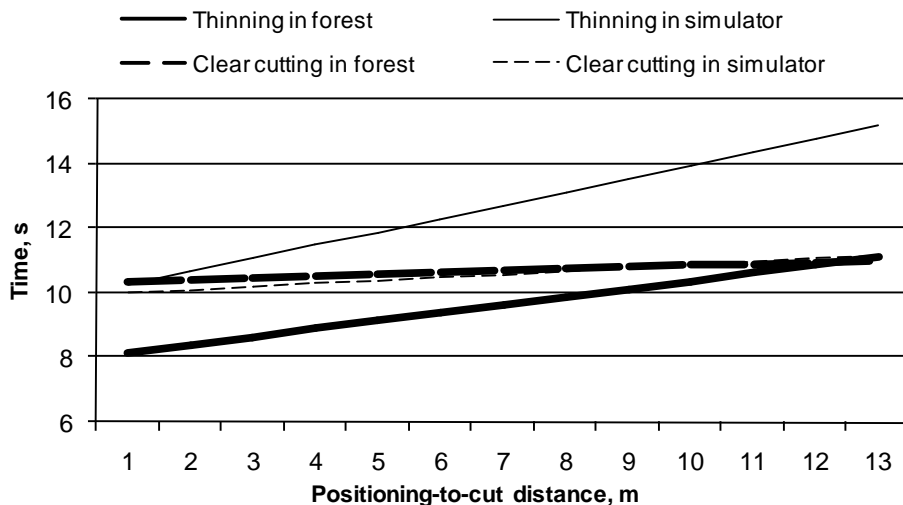
Figure 14. Effect of the positioning-to-cut distance to positioning-to-cut time.

In simulator thinning 83.8% and in forest thinning 79.1% of the harvested trees were removed from the front and obliquely from the side directions. The proportions were the same in the clear cuttings, while less than 10% of the trees were removed vertically from the side.

Felling with over 3 m moving took about 2 seconds more time than pure felling in thinnings (Figure 15a). In pure felling, the distance of the tree did not affect the felling time, whereas in felling with over 3 m moving the distance of the tree increased the total felling time. The difference between simulator felling and forest felling times with different methods was less than 2 seconds. In the simulator clear cutting, the dragging phase took less time than in the real forest (Figure 15b). Dragging of the tree on the ground takes more time and power when the mass to be dragged is large. A fault in the simulation of the dynamic forces, regarding the boom and stems, meant that trees of different sizes were moved at the same speed over the ground, this was also an issue for moving through the harvester head. On the simulator, the delimbing knives did not need to be tightly closed around the tree butt for the felling cut to start. Some operators took advantage of this characteristic, which sped-up their felling. If the harvester operator is not aware of this fault on the simulator, cheating in the felling phase can lead to a wrong work model.

a)

b)
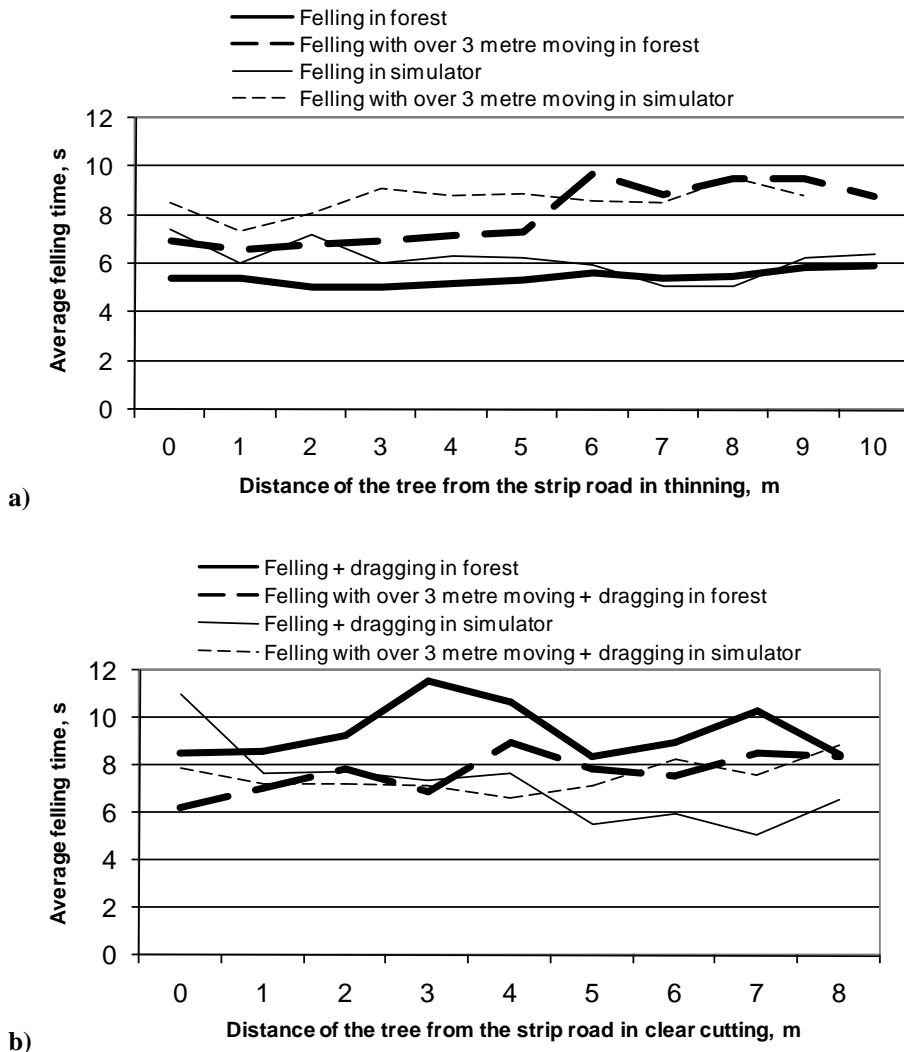
Figure 15. Effect of distance of the tree to felling time with different felling methods in thinning (**a**) and in clear cutting (**b**).

In both types of stands the proportions of felling directions for different distances in the forest followed the felling directions on the simulator. With long distances, trees were commonly felled away from the strip road, particularly in thinning. In addition, the trees on the strip road were felled away from the strip road rather than forwards. In clear cutting, only a few trees were reached from a distance of over 8 m; and of the total trees felled only a few were felled backwards.

In simulator clear cutting, processing, especially the feeding phase, happened too fast for larger stems and resulted in higher productivity (Figure 16). In thinning, the difference between the environments was not large, but in the clear cutting the difference regarding processing time was considerable, about 20 seconds. This can be explained as being due to the fact that operators did not need to control the quality of stems. The trees were without

defects; therefore the operators could crosscut according to the suggestion of the harvester. In addition, large stems could be processed far from the harvester. In thinnings, the time structures in the processing phases were very similar. The previously mentioned facts speeded-up processing, but the effect of 3-D visualization and the higher tree density slowed processing time down to the same level as in the real thinning.

In the simulator, the proportion of non-productive time was almost the same as in the real forest. However, it consisted of different kinds of simulator-specific time units compared to reality. Improvements in software would remove some of the defects, e.g. failed felling. Obvious changes in working technique, compared with the situation in a real forest, were not observed among the harvester operators in the simulator environment. Differences compared to reality can be explained mainly on the basis of the software elements of the simulator. In the main functions the operators used the same techniques as in a real forest.
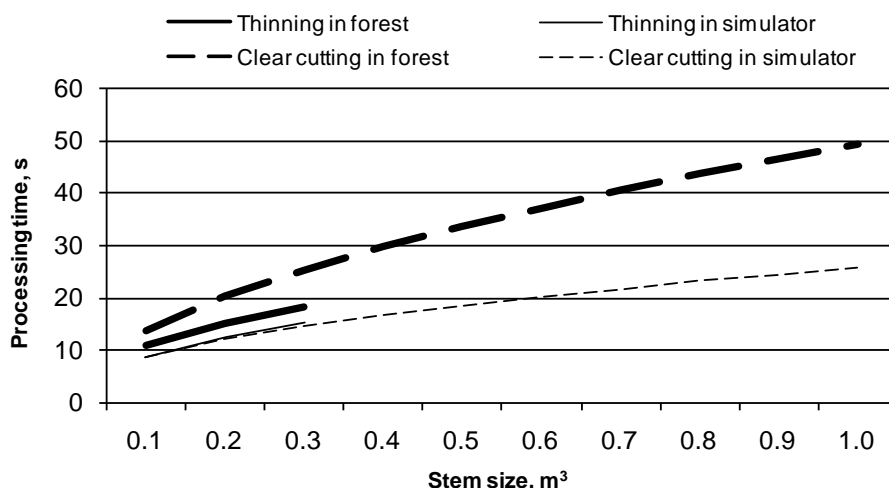
Figure 16. Differences in processing times as a function of stem size in the simulator and in the real forest.

3.3 Effect of edge trees on harvester positioning in thinning (Study III)

The most common working location for the boom base was 1.2m on the front side of the rear edge trees (as described in Figure 8). This mode class included 14.6% of all working locations whereas 49.9% of the working locations were at a distance class of 1.0 to 1.4m and 76.2% were in the range of 0.5 to 1.9m (Figure 17). The positioning seemed to be very consistent (p = 0.19 KW) with all the operators, which indicated that the harvester is usually positioned according to the rear edge tree. It was also noticeable that in the range of -0.5 to 0.4m little peaks appeared in the lines of proportions of working locations. In addition, distance values less than 1.2m weighted the total average distance between the boom base and rear edge tree closer to 1.0m than 1.2m. On both sides of the harvester, the right and left rear edge trees were located almost equally far behind the boom base. This was also the case for the front edge trees.
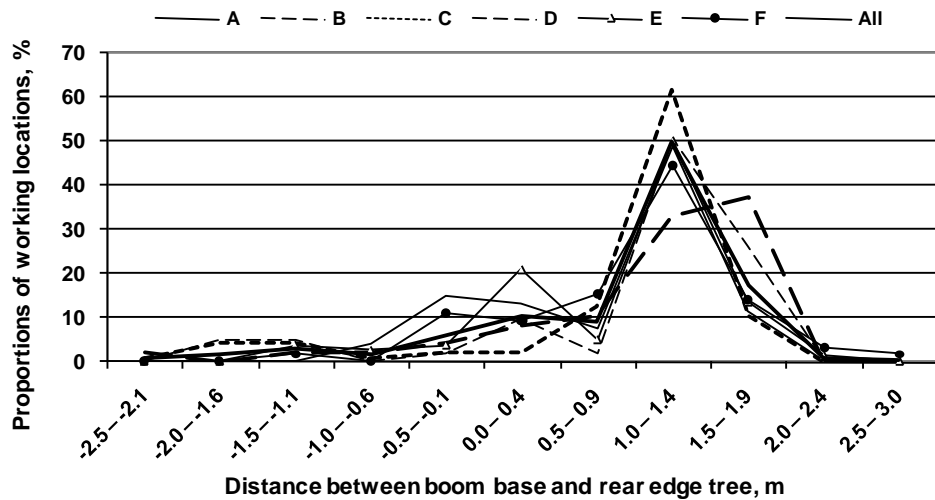
Figure 17. At a distance of zero the boom base and rear edge tree are side-by-side. If the distance is positive, the boom base is on the front side of the rear edge tree (as in Figure 8). The most common location for the boom base, 1.2m on the front side of the rear edge trees, is in the distance class of 1.0 to 1.4m. The lines for both individual operators (A-F) and the entire set (All) are shown.

A point pattern incorporating all felled trees was created (Figure 18). The size of the circle described the number of trees felled in the same location. The edge trees were located in their average locations, describing how the boom base is usually located according to the edge trees. In addition, Figure 18 illustrates how the locations of the edge trees varied in 95% confidence intervals in relation to the boom base. Areas T, the front sides of the front edge trees, were almost free of felled trees. This supported the idea that thinning on the stand side is performed in sequences of edge trees. Movement closer to or to the front side of the current front edge trees is needed to operate in the T areas. Operators naturally felled all trees from the strip road.
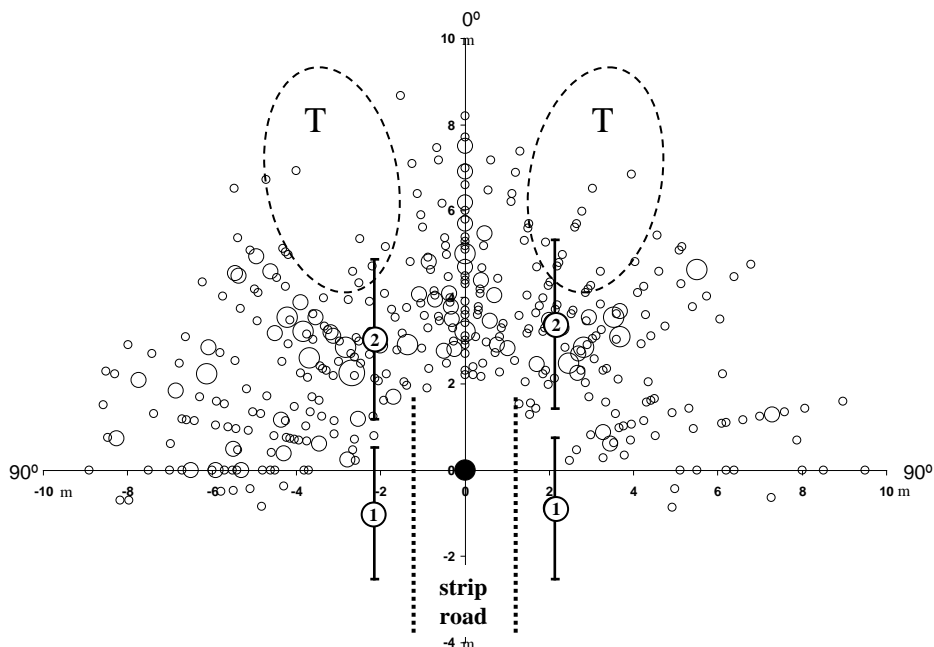
Figure 18. The locations of the felled trees in relation to the boom base, which is located at coordinates [0m, 0m], and the left rear edge tree at coordinates [-2.16m, -1.00m]. The size of the circle represents the number of felled trees in a certain location the smallest circle representing one felled tree and the largest four felled trees. Average locations (1 and 2) of the rear and front edge trees are marked with 95% confidence intervals. Areas T could not be fully thinned from this sequence of edge trees.

In the whole point pattern, the average felled tree locations (X) were in the oblique sectors, which meant that the usual working direction is focused there on the sides (Figure 19). The stand sides were divided into two equal sectors according to the front edge trees and the rearmost felled trees to determine whether the work was focused more on the oblique than the right-angle sector. However, the proportions of trees felled were almost equal in the oblique and right-angle sectors on the left side, so that cutting operations were concentrated almost equally in each sector. Since the right-angle sector reached further than the oblique sector, right-angle working sectors were used when distant trees were felled. The full slewing angle of the harvester was utilized during the work.
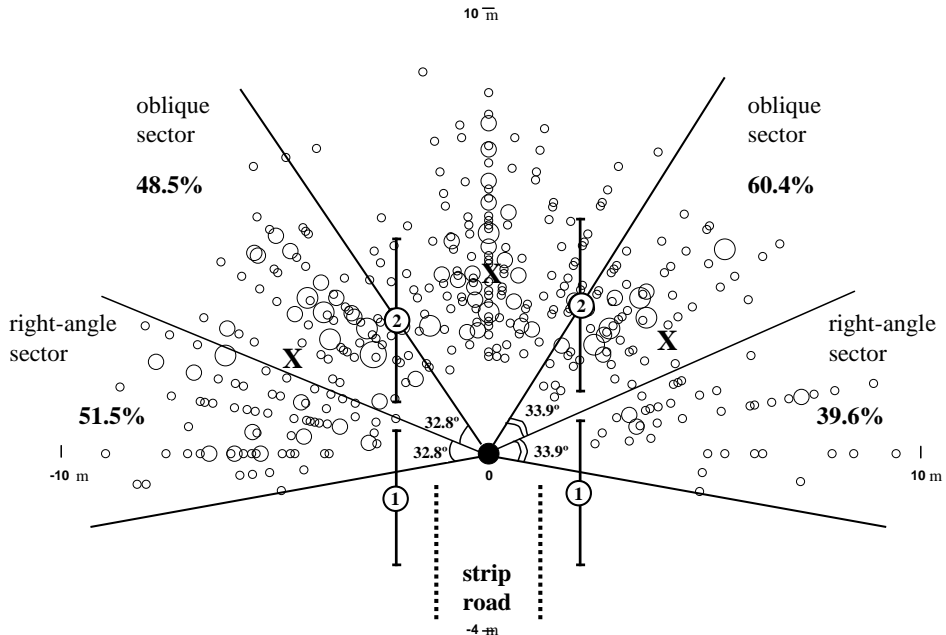
Figure 19. Percentage values represent the number of trees felled in the divided sectors on the stand side. Crosses marked the average felled tree locations on the stand sides and in the strip road. The average locations on the stand sides were calculated including only trees of that side and excluding trees in the strip road zone. The boom base is located at coordinates [0m, 0m].

Nearly half of the trees were felled in a boom base distance of 1.0 to 1.4m from the rear edge trees. There were also peaks in the range of -0.5 to 0.4m. Drawing the felled tree point pattern to include trees from the sequence of 1.0 to 1.4m shows that the trees are felled from the whole boom working area (Fig. 6a). In the range of -0.5 to 0.4m, however, the point pattern of the trees felled indicates felling of trees mainly from the strip road and the edge zones (Fig. 6b).

Ripley's K function was applied to each operator's point pattern and the entire data (Figure 21). The result indicated that the felled trees are located in clusters with all the operators, most strongly with operator D, since the $K(r) > \pi r^2$. Furthermore, the entire data was also clustered in this test. Clustering seems to be also stronger when the radius r grows. In harvester boom work clustering means that there are sectors around the harvester from which trees are felled.
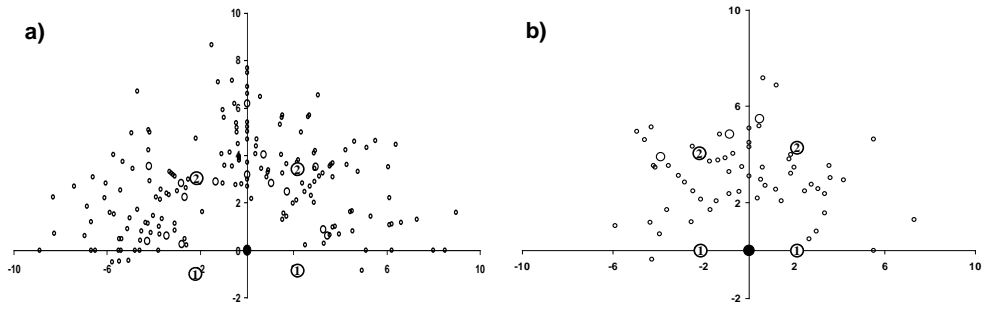
Figure 20. Trees felled in 1.0 to 1.4m (**a**) and -0.5 to 0.4m (**b**) ranges in relation to the boom base. The boom base is located at coordinates [0m, 0m].
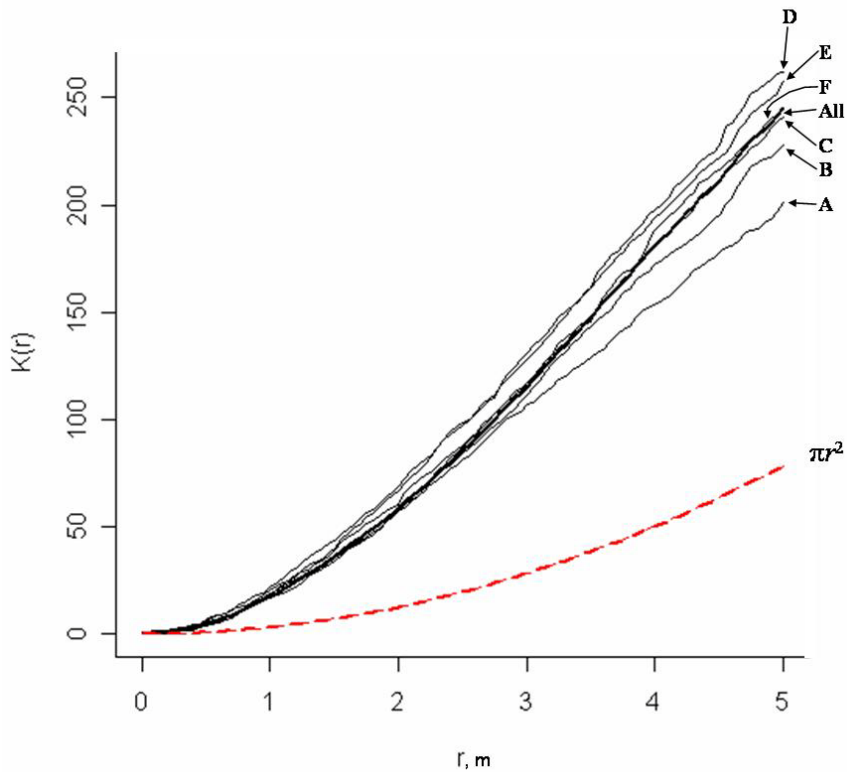
Figure 21. Ripley's K calculated for each operator and for the entire data. The dashed line presents the random situation (πr^2) and the solid line the calculated K(r). Operators' point patterns and the entire data are clustered, since the K(r) > πr^2.

The middle points of bunches of logs were also generally located between the sequence edge trees under 6m from the strip road centre (Figure 22). The average direction for the bunch was almost at right angles to the strip road. Trees felled on the strip road were processed beside the boom base, which increased bunch observations there. In the right-angled sector, operators moved distant trees closer to the strip road to be processed.
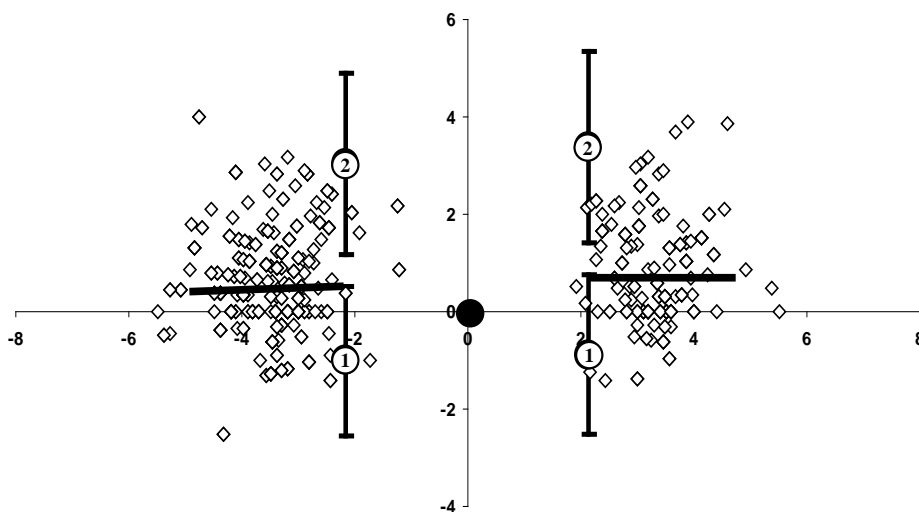
Figure 22. The locations of bunches of logs in relation to edge trees marked with spots. Thick lines present the average location and direction of bunches in relation to edge trees. The boom base is located at coordinates [0m, 0m].

3.4 Visuospatial cognitive abilities in single-grip timber harvester work (Study IV)

Harvester cutting productivity levels were higher in the 3rd compared to the 2nd class students with the most productive students even reaching the level of the professional operators. Reasons for the increase were higher levels of training and, especially, an ability to plan and predict the forthcoming work better. However, variation in productivity increased in the 3rd class compared to the 2nd class.

Operators' performance in memory tests (WMS-R) varied. The most productive operator performed normally, while not so productive operators varied on both sides of normality. On the basis of the results, no single area of memory could be identified as the most important, regarding productivity. However, from the viewpoint of productivity the whole memory capacity should be used effectively. Operators' high performance in verbal and concentration tests supported this conclusion. This indicated that comprehensive control of memory abilities and an ability to concentrate are characteristics for a productive operator. Also, there is some individual variation in the way of processing information; information can be coded as both visual and verbal stimulus.

The students' performance in psychological tests varied between the test, but on the whole they managed on an average level. In digit symbol and symbol search tests students performed below average, as did the operators, which can be explained by an aspiration to

work carefully. In addition, the digit symbol test, which measured mostly perceptual speed, correlated negatively with the productivity among students and the same correlation was also low with the operators. Productive operators performed also well in the matrix reasoning test, which measured perception of details and attention. In general, the operators reached higher points in the organization of perception (POI) than in speed of perception factor (PSI). In addition, hand-eye coordination in connection to speed seemed to only slightly explain productivity, as also speed of perception. These results confirmed that the perception of details and entirenesses, non-verbal deduction, spatial perceiving and concentration are more important from the viewpoint of the operator's work and productivity than speed and accuracy although those can not be fully excluded.

This study indicated that productive operators had a combination of well controlled cognitive abilities. Productive operators also considered work processes more widely. To sum up, this study confirmed that comprehensive perception, wide use of memory functions, non-verbal deduction, spatial perception, coordination, concentration, motivation were characteristic of a productive operator. Verbal ability can also be an important ability depending on the coding of the stimulus. Spatial perception was a central ability. Fast perception and visuomotoric abilities are important in harvester work.

4 DISCUSSION

The principal objective of this research was to discover and describe a productive working technique for harvester work in first thinning. On the basis of main observations found in Studies I and III the productive working technique is described and justified in chapters 4.1 – 4.3 with references to other studies regarding similar research issues. The description of productive working technique starts with effective positioning of harvester on the strip road according to the edge trees (chapter 4.1). The next phase is the determining of felling direction for a removable tree, which is influenced by the tree distance and location from the strip road (chapter 4.2). After the selection of felling direction the stem is processed close to the stump or moved some other place for some reason. The necessity and performance of felling move and steering of harvester head to next removable tree is discussed in chapter 4.3 using the principle of minimal movement working technique. The figures in chapters 4.1 – 4.3 are plans of action of upcoming boom work, so they can be understood also as some kind of illustrations of schemas on a working location level.

Working technique is one part of the entirety of harvester operator training and can be approached in many ways. The other objectives of this research were to improve harvester operator training by highlighting the problems of harvester simulators and discovering the important cognitive abilities needed in harvester work. For this reason the working technique of harvester simulator was compared to the working technique of real cutting situation and the possible problem spots of the simulators and simulator training were brought up in Study II. In addition, typical cognitive abilities of productive operators were studied with psychological tests in Study IV. The usability of harvester simulators in the training of working technique is discussed in chapter 4.4 including the features of the productive working technique and cognitive abilities. The connection of schemas is also presented in this chapter. At the end of the discussion the research and the usability of the results is assessed and the needs for future research are considered.

4.1 Positioning a harvester effectively in a relation to edge trees on the strip road

In Study III the results indicated that there is one "main working location" in one sequence of edge trees (Figure 23a). The felling and bunching of most of the removable trees from the stand side is performed from the main working location (Study III, Figure 17). In this location the rear edge trees do not restrict the movements of the boom, and the harvester is not placed too close to the front edge trees since the boom movements would be restricted and the operator has a good field of vision to the stand side. Trees on the strip road are also felled in order to free working space for the harvester head and boom enabling the moving of stems over the strip road and steering the harvester to a new working location (Study III, Figure 20a). On the basis of the average felled tree locations on the stand sides, the boom work was directed more obliquely than the right-angle sector (Study III, Figure 19). Clustered point patterns confirmed the idea of sector working (Study III, Figure 21), which was shown also in the study of Ranta et al. (2004). In addition, operators' similar average driving distance between working locations in Study I Table 4 illustrates the same kind of moving method.
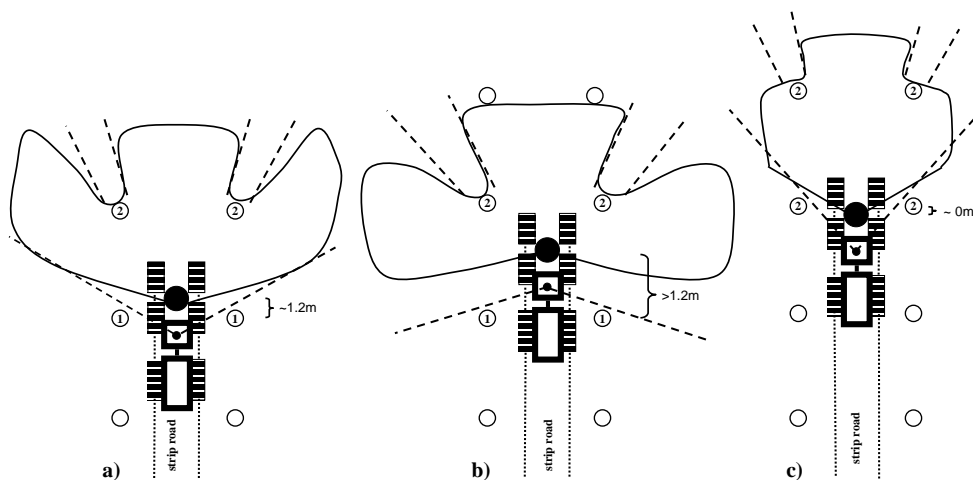
Figure 23. Progress of harvester work in thinning where edge trees are located opposite to each other with even distance (opposite case). Main working location (a), auxiliary working location (b) and preparatory auxiliary working location (c). Solid line presents possible boom working areas and dashed lines the operator's field of vision.

After the main working location, the harvester is driven forward, and "auxiliary working locations" are needed if removable trees are unreachable from the main working location (Figure 23b). These locations can vary in relation to the removable trees on the stand side, but are generally located closer to the front than the rear edge trees. Since trees at long distances can be reached and felled most easily at right angles, generally the working angle is more right-angled in these locations. Ranta et al. (2004) also observed that operators have another location from where the distance trees are felled more right-angled.

There were also observations of working locations where the boom base and the rear edge tree were almost side-by-side (Study III, Figure 17). This indicates that in these locations the strip road is opened further to the front side of the line of the front edge trees (Study III, Figure 20b). Trees are felled from the upcoming edge zones so that there is free space to locate the bunches of logs coming from the next sequence of edge trees. This location can be seen as a "preparatory auxiliary working location" before moving to the new main location to the next sequence of edge trees (Figure 23c).

The harvester is driven forward after working the main, auxiliary and preparatory auxiliary working location and performing cutting operations on the stand sides and the strip road. Generally, trees from the strip road are felled in all the working locations because the number of removable trees is larger (removing density is higher) on the strip road compared to the stand side. The new main working location is located on the front side of the front edge trees. The more the stand side opens up for the boom work the more the line of the front edge trees (a gate to new sequence of edge trees) is passed. The previous front edge trees (2) now become rear edge trees (1). In the new main working location, the operator chooses the new front edge trees to be left along the side of the strip road at no later than the beginning of cutting operations.

Previous description of locating of harvester bases on the restriction effect of the edge trees. The main reason for this kind of locating is that the front edge trees restricts the boom operations on the front sides of these trees, additionally, the front edge trees restricts the operator's field of vision in those areas. For these reasons those areas (marked as T in

Figure 18 in Study III) could not be fully treated from the previous sequence of edge trees/previous working location, which leads to sequential working according to edge trees.

The location of bunches of logs in relation to edge trees strengthened the idea that the thinning on the stand side was performed in sequences of edge trees (Study III, Figure 22). In the best case, the edge trees chosen are located opposite each other, on either side of the strip road, and three working locations are needed in a sequence of edge trees (as the case in Figure 23). In a dense forest, the operator has better possibilities to select edge trees since the number of edge tree alternatives is larger. However, usually the harvester must be positioned according to the sequence of edge trees of the side on which the cutting operations are performed next in course. In a case where the edge trees are located at regular distances along the side of the strip road, but not opposite to each other on either side of the strip road, the positioning of the harvester can be done in a similar way except the processed area on different sides depends on the edge tree location in relation to the boom base. The same working locations, as previously presented, are possible to discover from the non-opposite case (Figure 24).
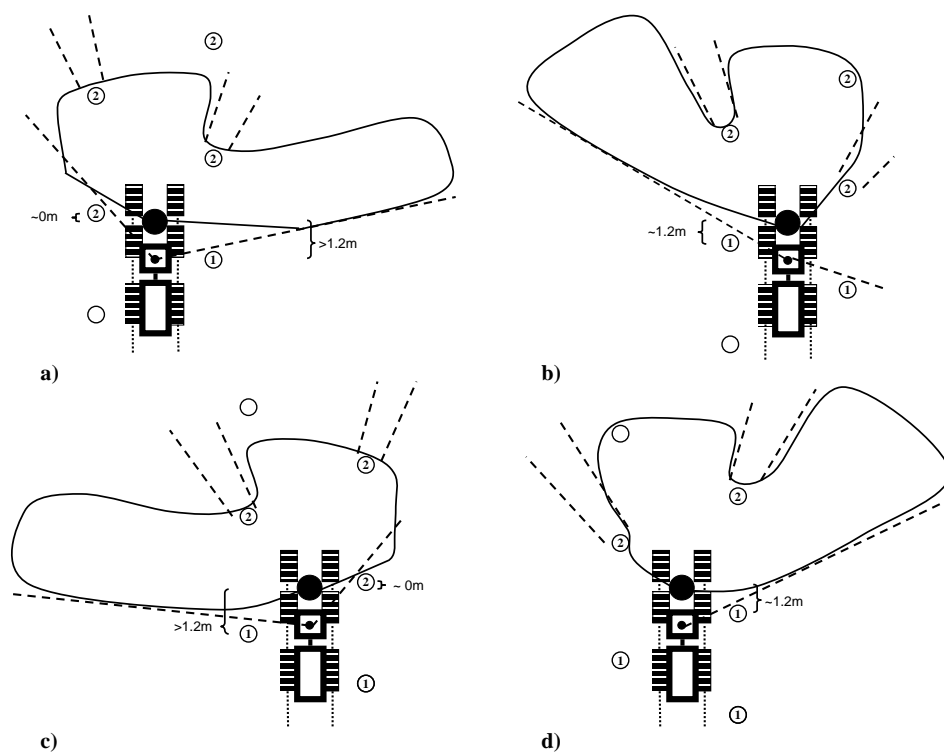
Figure 24. Progress of cutting work during thinning where edge trees are located at regular distances, but not opposite to each other (non-opposite case). Preparatory auxiliary working location for the left side and auxiliary working location for the right side (a), main working location for the left side (b), preparatory auxiliary working location for the right side and auxiliary working location for the left side (c) and auxiliary working location for the right side (d). Solid line presents possible boom working areas and dashed lines the operator's field of vision.

In the non-opposite case the sequence of edge trees also requires three working locations. However, the harvester is positioned simultaneously so that it can operate on both stand sides. In the first case, the auxiliary working location and the preparatory auxiliary working location are joined, and cutting operations are performed on both stand sides. (Figure 24a and c). In the second case the harvester is positioned to the main working location, where the other side of the working area is processed since the other side is restricted physically and visually by the edge tree (Figure 24b and d). In the non-opposite case the number of working locations is the same as in the opposite case but the working sectors differ according to the edge trees.

4.2 Processing a tree effectively in a working location

After the harvester has been positioned in the working location, removable trees are felled and processed into logs from the strip road and the stand sides. The work phases needed to process a tree on a log pile in the tree handling cycle are steering the harvester head to the next tree, felling cut, felling in a suitable direction and processing in a suitable location. On the basis of general ways to increase productivity, the unnecessary work movements should be minimized or removed completely from the work phases (ILO 1981, Harstela 1991). Therefore, in a question of harvester work, unnecessary boom movements should be removed, which in practice means that the positioning distance and the moving distance of a stem after felling cut should be short in a tree handling cycle. This technique is here called "minimal-movement working technique". Study I proved that the most productive operator minimized these distances. In other words the harvester head should be kept "loaded" with a stem as much of the working time as possible.

In Study I the proportions of felling directions were observed on different distances. Felling has been found to be the work phase were damage to trees is more likely (Athanassiadis 1997, Sirén 1998). The remaining trees, the distance of the tree to be felled from the harvester and the place of the pile influence the felling direction. As seen in the results (Study I, Figure 12, top figure), the further a tree was located from the harvester the higher was the away from the strip road -felling proportion (Figure 25, trees 3 and 4). In practice this means that the tree is felled to the direction of a boom. A rational explanation for this is that if the operator wants to move the tree closer the strip road after felling, the only way to move it is the boom direction because in other felling directions the tree is felled behind the other trees, which hinder tree moving. This fact is valid also in a case of strip road trees that are situated far in front of the harvester: a tree must be felled to the direction of boom/strip road if it is necessary to move it. In addition, the operator should always be able to see in the direction of felling to enable felling with minimal damages. The operator sees often best to the direction of boom on high distances.
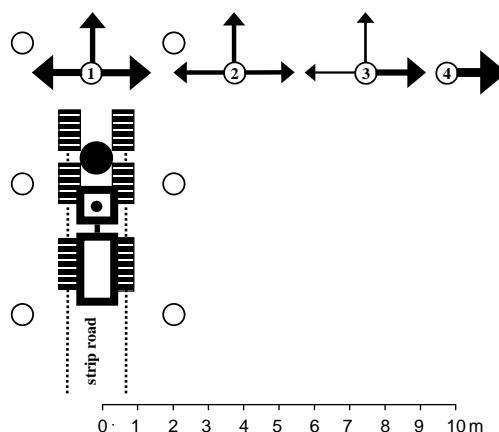
Figure 25. The most used felling directions on different distances from the strip road. The thicker the arrow the more used felling direction. Felled trees and they locations are marked with numbers 1-4.

The closer a removable tree is to the strip road the more choice there is regarding felling directions; the remaining trees do not limit operators view much or the boom movement, furthermore, boom is more powerful, and also the open area of the strip road encourages felling in that direction. Therefore, trees on the edge zone (Figure 25, tree 2) have many possible felling directions. In this location the away from the strip felling direction was only a little more favorable than toward the strip road or forward felling directions (Study I, Figure 12). Felling towards the strip road is favorable, since there is free space to fell unless the edge trees on the pick up side hinder this. However, in felling towards the strip road, felling to the correct place is more difficult than felling to the front or away from the strip road.

Strip road trees were felled mainly in two directions: away from the strip road or forwards parallel the strip road (Figure 25, tree 1). The felling direction depends largely on the operator's work habits, which was seen in the large variation in felling directions on the strip road among the operators (Study I, Figure 12). Felling away from the strip road was favoured by the operators who preferred the log piles to be at a direct angle to the strip road. Forward felling was favored by the operators as they wanted to avoid damaging the remaining trees in the side areas. In forward felling, the strip road trees are often damaged, however, those trees are removed in any case. Therefore, felling along the direction of coming strip road has been found to decrease damage (Sirén 1998). Log piles will be at an oblique angle to the strip road in forward felling and also more often behind the edge trees. As a conclusion, felling in a direction away from the strip road is beneficial because of the better log pile angle for the forwarder, correspondingly, the forward felling direction is beneficial because of the lower levels of tree damage, however, with a little decrease in forwarder loading productivity.

4.3 Moving of tree after felling cut

As stated previously the minimal-movement working technique calls for short moving distances of trees after the felling cut when moving trees to the processing place. In

processing, logs are typically piled in the edge zone (Study III, Figure 22), therefore, depending on the tree location, some trees must be moved more than others to reach this area (Figure 26). Strip road trees (Fig 26, trees 1 and 2) must be moved, at least a little, in any case to move them off from the strip road. If the strip road tree is close to the harvester (1) it has many possible processing places and feeding directions. In this case the moving distance is generally short.

If the strip road tree is located further in front (Fig 26, tree 2), it can be dragged to the side of the harvester or processed away from the strip road, near its growing location. In the first case the felling direction is forwards and the dragging distance is far. In the second case, the felling and processing are performed in an area where the operator's view is often restricted (Study III, Figure 18). In a stand with a high tree density, the first case is preferred: the tree is felled in the direction of the strip road, if the top of the tree gets stuck, moving the tree will release it, and the operator is able to see to the felling direction. The amount of damage will also be smaller. To obtain log piles in direct angle to the strip road the second case is preferred.

Removable trees in the edge zones (Figure 26, tree 3) should be processed near the stump, as a result the moving distance will be minimized. Trees can be fed to many directions in processing, depending on the felling direction, but the most effective is feeding the tree towards the boom base under the boom. This felling direction is suitable from the perspective of the operator's view and the feeding direction is free of other trees. In a stand with a high tree density, moving an edge zone tree over the strip road can be faster than attempting to fell the tree harshly at the stump. Therefore, a tree should be moved over the strip road from the edge zone only if it is faster than felling at the stump. A tree can be fed also away from the strip road utilizing the free space on the strip road in felling. However, in this case the probability of tree damage in feeding will increase since the operator's view of the stand side between the remaining trees is limited.
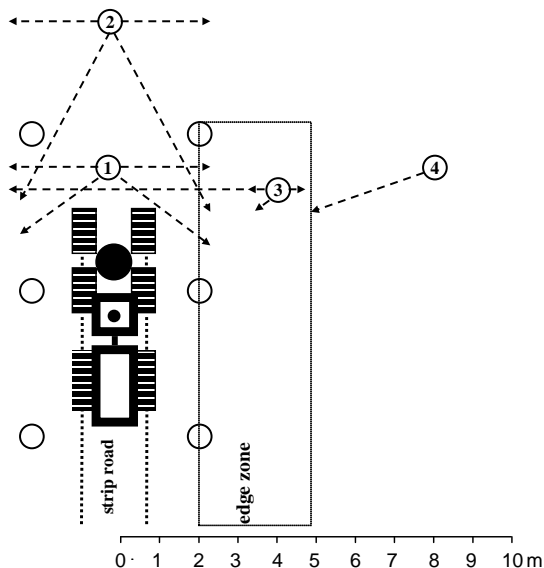

Figure 26. Moving stem to the processing place. Felled trees and they locations are marked with numbers 1-4.

As seen in Study I Figure 12 distant trees were generally felled away from the strip road in the direction of the boom. In this case, from the viewpoint of tree processing, the only beneficial moving direction for the distant tree is towards the harvester and processing under the boom towards the boom base (Fig 26, tree 4). In other processing directions the prospective log pile will be at such an angle behind the remaining trees that it is unfavorable for the forwarder operator. In a stand with a high tree density, hindering free felling, a tree can be moved to the side of the edge zone and process there towards the strip road. In other cases the distant trees should be moved closer to the strip road only during the felling moment. Felling moment is then utilized effectively. This kind of working technique minimizes moving distance. In addition, pile distance from the strip road has not been seen to significantly influence loading time if the pile locates further from the strip road (Tufts 1997, Väätäinen et al. 2005).

On the basis of Study III Figure 22 the operators piled the logs mainly in the edge zones by moving the distant trees closer. When minimizing positioning distance to the next removable tree, the location of the processing place should be taken into account since the positioning is performed typically after the processing work phase unless the operator does not drive forward. Therefore, the next removable tree should be located close to the previous processing place. A tree can be moved in felling so that it comes closer to the strip road but only if the positioning distance to the next removable tree will remain short. In addition, this enables processing of at least two trees onto same pile also making the grip load size larger for the forwarder. Grip load size near the lifting maximum is the most beneficial for the forwarder in terms of productivity (Gullberg 1997, Väätäinen et al. 2006). Naturally, the next removable tree should be taken from that edge zone side where the processing occurred.

An ability to plan the processing order of the removable trees enables minimal-movement working technique. The idea of sector working is beneficial in this context by focusing the work on one working sector at a time thereby making the working environment smaller (Ranta et al. 2004). Working on one sector at a time, makes the moving distances of harvester head to a tree or the moving distance of a tree in felling inevitably short. However, in some cases moving the tree over the strip road speeds-up the work if the top of the tree gets caught in other trees. Due to this move, the next positioning should be aimed at the processing side.

The need to move stems after felling has been found to increase cutting damage on the remaining trees (Sirén and Tanttu 2001). From this point of view minimal-movement working technique is beneficial since the stems are moved only as much as is necessary. In addition, stems are mainly processed on the stand side, which reduces the amount of cutting damage on the trees on the side of the strip road, where the damage probability is highest (Fröding 1992, Granhus and Fjeld 2001). In this case, feeding of stem occurs also under the harvester boom where the harvester operator has good visibility.

Previous kind of minimal-movement working technique does not necessary bring sufficient branches and tops of processed trees to the strip road to increase the bearing capacity of the ground and thus decrease depression and root damages in thinning. The use of good branch mats may reduce the depth of the strip road depressions by half (Fries 1974, Brunberg and Nilsson 1988). In the minimal-movement working technique, trees are processed typically at the stand side with the branches and tops of the trees being left there. Considering Figure 26 from the bearing capacity point of view, the change in harvester head movement technique occurs especially on trees 3 and 4: the branches and tops of those trees must be moved to the strip road or the trees must be moved over the strip road to get the branches and tops to the strip road. A more rational method of these is to move the whole tree over the strip road, therefore, extra grabbing movements to position the branches

and tops to the strip road are not needed. A reasonable number of stems can be brought to strip road without significant increase in time consumption (Sirén 1998).

The harvester and forwarder have different levels of productivity with the variations in stem size having a larger effect on the harvester than on the forwarder's productivity. Especially in first thinning, the stem size is small resulting in the productivity of the harvester being considerably smaller than the forwarder (McNeel and Rutherford 1994). In practise this means that at the same time the forwarder carries more wood to the roadside than the harvester cuts. Since the influence of the harvester on the productivity of harvester-forwarder chain is larger the productivity of the whole chain should be controlled by the harvester (Tufts 1997). Pile size has been found to influence the productivity of a harvester considerably: when the pile size decreases, the number of loadings increases which means that the productivity of the forwarder decreases (Gullberg 1997, Väätäinen et al. 2006). In the minimal-movement working technique the pile size is small if the felled trees are processed close to the stump and piled there. Therefore, the minimal-movement working technique balances the productivity differences of chain of harvester and forwarder in first thinning. It is usually possible to process trees from one working sector onto the same pile, which increases pile size inevitably.

4.4 Teaching of harvester work in thinning and cognitive abilities

A harvester simulator is a practical tool for studying the previously presented working techniques of thinnings. Positioning of the harvester on the basis of edge trees, and the suitability of different felling directions on different distances and harvester locations in relation to edge trees can be trained. During these exercises a student learns to work in a plane, where harvester head movements are limited by remaining trees. Study II illustrates that the simulator allows students to become more aware of the realities of their surroundings while using the harvester. An ability to choose appropriate working technique for the situation in question will be enabled. In addition, in the simulator, the same cutting situation can be repeated thus the trainee has a possibility to practice different kinds of working techniques in the same cutting situation.

Nowadays, harvester simulators are widely used in addition to real harvester training to increase student's sensomotoric harvester handling skills and the knowledge of the harvester's information systems as well as to reduce training costs (Ranta 2004, Parisé 2005). The benefits of harvester simulator training have been shown in numerous studies (Freedman 1998, Wiklund 1999, Yates 2000, Hoss 2001). However, the limitations of harvester simulators should be noted, as they might create incorrect habits among the trainees. As found in Study II the simulator had differences to reality in many of the work phases. Many of these faults are observable, but if most of the training hours take place in the simulator, the possibility to adopt an incorrect work model exists. The selection of an appropriate working technique is more correct if the students are more aware of the faults of the simulator. One way to avoid unconscious wrong work models is to create more realistic simulators.

Significant differences in productivity can also be explained through the schemas. High level schemas are based on symbolic signs where verbalization is one area (Rasmussen 1986). In Study IV harvester operators performed well in the verbal tests, which gives hints that schemas are used in harvester work. Some operators develop more effective ways of observing and orientating to changing work situations than others. In other words, productive operators have the capability to change schemas according to the situation. This

explanation corresponds with the common concept of the meaning speed in harvester work. Speed is an integral part of the work, but it is not necessarily an independent ability. Therefore speed is partly dependent on the selected schema and the adequacy of the schema for the situation (Figure 27).

The careful planning of exercises and educational methods, as well as the overall connection of the exercises to whole curriculum, are very important in simulator training (Regian 1996, Wiklund 1999, Ranta 2003). In addition, cognitive abilities are a part of the overall learning and growing into the job, for this reason they should not be omitted from the training. Study IV found that to become a skillful harvester operator it is apparent that the mastering of different kinds of cognitive abilities is more important than just one or two. The meaning of schemas also was an issue, as found in other studies (Gellerstedt 1993, Tynkkynen 2001a, Ranta et al. 2004, Kariniemi 2006). In addition, many of the students' weaknesses may be due to poor planning skills, students need information on what are the key features of the productive work process (Study IV). One solution for this is the transfer of tacit knowledge to the students, which would help in their adoption of the schemas. Therefore, if the harvester positioning method of Study III, which is tacit knowledge at its deepest, and a methodology of how the harvester work proceeds in thinning are joined, a student will adopt at least one productive working technique during the harvester operator school. Through this the student will also adopt the schema of that specific working technique when the related cues (as in Figure 27) from the surroundings are automatically observed enabling more productive work movements.

The described methodology is also in connection to work planning skills enabling the student to plan the forthcoming work so that interruptions are minimized and the work functions would be more productive. The teaching of skills and abilities is almost an impossible task, because most of them are inherent at birth. However, work planning skills are possible to improve in the short term (Study IV). For example, where the harvester working locations should be located on the upcoming strip road. Awareness of being in the right working location speeds-up the learning process considerably since it has been found that through the learning-by-doing method it takes several years to place the machine in the optimal position (Gellerstedt 2002). In addition, in exercises, the focus should be on learning goals instead of performing when the task specific cues, which are related to certain goals, direct the attention to the task at hand, and help to filter out the goal-irrelevant information (Saariluoma 1985).
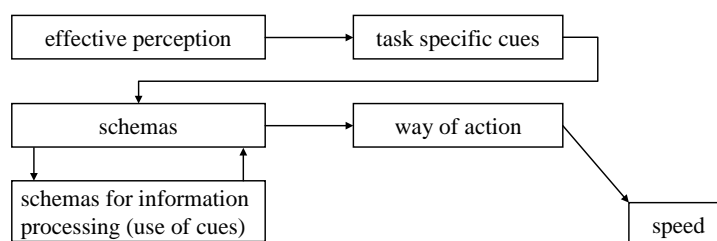

Figure 27. Forming of way of action and speed in harvester work.

The tests used in Study IV are suitable for assisting in the selection of harvester operators since the productive operators performed quite well in most of the tests. However, general tests to determine the specific abilities, as used in the study, can be too general. Therefore, some important work specific details can be missing. Hence, the best test result would be reached when the tests would include features of that work to which they are designed for. However, in that case, the tests would support persons who have experience of harvester work. So when selecting students to do the school general test, the tests are more suitable when the students are at the same level but when selecting operators from a group of experienced operators the test could include work specific features. As a result the test result would be more accurate.

To conclude; harvester operator's work performance is a sum of many factors and developing only one side of work the productivity will not increase considerably. Instead, the objective development of all characteristics will lead to a better result (Study IV). In addition, the harvester work is today more mentally than physically straining (Nåbo 1990, Gellerstedt 1993, 1997, Tynkkynen 2001b, Berger 2003, Ranta et al. 2004). This should also be taken into account already in the operator training when the harvester operators' would have comprehensive capabilities to handle mental strain, especially in thinning, where the working environment is more complex and demanding compared to clear cutting. This would also increase the meaningfulness of the work if the operator has prepared for this.

4.5 Assessment of the research

4.5.1 Relevance

Currently, the forest management situation in Finland is such that the estimated annual need for first thinnings is 250 000 hectares per year (Anon 1999). During the 2000's, however, only 170 000 – 190 000 hectares were thinned annually, which leads to an unbalanced situation in thinning-based forest management (Juntunen and Herrala-Ylinen 2007). According to the latest forest inventory calculations (Korhonen et al. 2007), the target for first thinnings should be around 300 000 hectares per year during the next ten years to return to the normal annual thinning levels. From this point of view, and the difficulties concerning thinning cuttings in general presented in chapter 1.2.2, all developments in this area are welcome.

The results of this study support the principal objective of the research since a productive working technique for harvester work in first thinning was discovered and described. The main observations were that the moving distance of the harvester head should be minimized in positioning-to-cut and felling work phases. Reversing should be avoided and the clearing time should be minimized. These matters are easy to measure and control in practice. In addition, to improve harvester operator training the problems of harvester simulators were presented when those matters are easier to point out to the students in the training, thereby, avoiding picking up incorrect work models. Psychological testing finalized the data collection and revealed that harvester operators do not need to have any superior ability to become a productive operator. In the operator training it is important to highlight the observation of relevant things from the harvester's surroundings when correct and significant information is received for work planning.

As with previous studies (Sirén 1998, Ryynänen and Rönkkö 2001, Kariniemi 2006, Purfürst and Erler 2006) this research has shown that the harvester operators cause large

variations in productivity. On the basis of this study material Väätäinen et al. (2005) calculated that the working technique would explain 10 to 15% of the variations in productivity. If the improved working techniques could increase productivity that much it would be a significant improvement. The results of this study are noteworthy when implementing the basics of productive working technique to the education of harvester operators. Combining previous kinds of work technical features with the training of operators the learning and the development of productivity would be boosted. The education at the harvester school would produce more productive and work ready operators, thereby decreasing the harvester contractors' reluctance to hire young operators. In addition, the option that a professional harvester operator is consulted, with regards to the correct working technique, should not be excluded. This could also improve the abilities of the less able operators' and thus making it more interesting for the contractors.

The remaining productivity differences originate from the operator's cognitive and sensomotoric abilities. As stated previously, natural abilities are very difficult to teach so the focus should preferably be directed to factors that can be easily improved such as the development of work planning (Kariniemi 2006), creation of schemas and skills to distribute the working location into suitable working areas (sectors) (Ranta et al. 2004).

4.5.2 Validity and reliability

There exist three methods to find the best working technique. In the first method the best working technique is chosen from the existing ones. In the second method, the best work phase techniques are selected from the existing working techniques, measured and examined, and joined together creating a new working technique. In the third method, a totally new method to work is created and evaluated. In the first method, the different kinds of working techniques are found by reading studies, books, interviewing operators and persons in the field, etc., and finally listing the different working techniques and the factors that separate them from each other. After this, many operators performing their work with these specific working techniques are selected for field experiments and the methodology of comparative time study can be used (Harstela 1988), and the best working technique is found. However, even though this is the most used method nowadays this method does not elicit the best working technique. In this case, the most productive working technique is not created, instead, it is selected from the existing ones, when it can include non-productive work movements. In the second method, the view point is in one work phase at a time. It means that the specific work phase is measured and observed, and when the operators use different working techniques in different work phases the best of the work phase techniques are selected to the final working technique. In this method, the working technique is created joining the best work phase techniques. One must, however, ensure that the best work phase techniques construct a rational continuum. This method has been seen to be impossible to implement or not sensible in varying forest conditions (Harstela 1991), however, nowadays, as cutting work is performed almost solely with machines, the influence of forest conditions on work performance is smaller and the harvester is capable of collecting exact work process data automatically, the use of the second method is reasonable. For these reasons, the second method was followed in this study. The third method will be in question when a totally new machine is designed.

Since the working technique was the main focus of this study, the movement/consumed time of the harvester head was measured in each work phase. For this reason, the time study method was used to measure the work phase times together with the working technique observations. So the work study included two data collection methods to measure the work

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performance of the harvester operator: time study and working technique observation. The measuring unit of time study (second) is dependent on the worker's rate, which for time is not a valid variable to measure harvester head movement in the working technique in mind. The operator's influence is involved, which means that the measured time can be the same although the moving distance of the harvester head is different in different situations. In addition, different operators have different rates, therefore a reliable comparison is difficult. The influence of rate can be decreased by comparing the values of the same operator. For this reason, harvester head movement was estimated also in meters, which is dependent on the operator's working technique, but is independent of the operator's work rate.

In the working technique observation, the data collection was based on visual estimates. The base for the work technique observation method was obtained from Sirén (1998). The distances of removable trees and processing locations were estimated at a vertical angle from the middle line of the strip road with an accuracy of 0.5 meters. The main reason for this was that the observer had to stand in a safe place where the work could be seen without restrictions. The best location was either in front or at the side behind the harvester. Utilizing the angle and position of the boom it was possible to determine, quite reliably, the distance estimates. However, felling direction was estimated on a nominal scale (classified) so one of the felling directions had to be chosen for each felled tree. The problem was the trees that were felled in the border line of two felling directions. In this case the class to which was closest to the felling direction was chosen.

Almost all the variables in the working technique observation were estimated on a nominal scale. Instead, more exact results and analysis would be reached by measuring/estimating the variables in interval or ratio scales. Therefore, pick up and felling direction classifications should be replaced with pick up and felling direction estimates/measured values in degrees. In the moving distance of the harvester head, the actual moving distance should be measured, not calculated based on tree stump and processing place locations. For these reasons, the working technique observation in harvester work should include variables described in Table 6. In this new method compared to the one employed, the distance to removable tree and the distance to processing location are estimated/measured from the boom base. Since the harvester head's movements are primarily two dimensional (Branczyk 1996), the meter variables are measured in Euclidian distance (two dimensions).

Table 6. Variables for harvester working technique analysis.

Observations per tree
1. Pick-up distance from the previous processing place or from the strip road if harvester moved after previous stem, meters
2. Pick-up angle in relation to direction of motion of harvester (strip road), degrees
3. Distance to removable tree from the boom base, meters
4. Felling direction angle in relation to direction of motion of harvester (strip road), degrees
5. Moving distance of tree from stump to first crosscutting location, meters
   - The proportion of the stem moved in vertical position separated in the moving distance
6. Angle of boom in relation to direction of motion of harvester (strip road) in processing, degrees
7. Distance to processing location from the boom base, meters
8. Driving backward and forward during a tree, meters

Observations per moving to a new working location
9. Forward and backward driving distances from previous working location, meters

The most exact values for the working technique observation would have been received by using different kinds of sensors to define the position of the boom in different work phases. In this case the distance estimates would have been replaced with exact distance values and positioning and felling classes with positioning and felling degrees. The used estimation accuracy appeared sufficient regarding the boom work. However, exact positioning and felling angles would have increased the accuracy, thereby enabling more versatile calculations as seen in Study III. In addition to working technique observation, the time study was also based on ocular estimation since the starting and ending points of the work phases were observed visually. However, this seems to be acceptable since numerous studies have been performed with the same method. In this study, an automatic data collecting device was also used. The manually collected time study data was compared to that and the difference in main work phases was very small (Väätäinen et al. 2003). In both data collection methods, working technique observation and time study, the vigilance and experience of the observer is vital. The same two observers were used in all data collections where these methods were used. On the other hand, the whole data could have been videotaped and subsequently examined in laboratory conditions, and reached a higher level of accuracy that way, but the number of working hours would have doubled and the faults in stereoscopic effect on TV screen might have confused distance estimates to some extent.

4.5.2 Generalization of the results

This study focused on one harvester model only. The positioning of other type of harvesters in relation to edge trees in the strip road is different as are the working sectors on the sides, however, the edge trees are as meaningful since they would be noticed in the same way. Positioning of harvester on the basis of edge trees has not been previously studied. Instead, the placement of the cabin in relation to boom base has been studied from the productivity point of view without proving the importance of edge trees in different cab-boom base constructions (Scherman 1985). On the basis of this study the most appropriate working location estimates for other types of harvester can be concluded.

The minimal-movement working technique is also applicable for other types of harvesters when the thinning work is performed with a 10m long boom. It is based purely on minimizing the unnecessary movement of the harvester head. The presented working and visual sectors of the harvester boom are dependent on the machine structure so those can not be generalized to harvesters that have significantly different kinds of structure. Instead, felling directions on different distances do not differ significantly between different kinds of harvester types since the remaining trees are setting restrictions on the work in the same way. The edge trees must be taken into account independent of the harvester type in positioning the harvester on the strip road, however, this is dependent on the harvester type. In addition to previous issues, harvesting circumstances influence the working technique, which for the results of this study can be generalized for first thinning stands where the density of trees is normal and the terrain is quite even.

Six professional harvester operators were studied in this study. The aim was to determine the reasons for differences in working technique and productivity. To justify these matters, the number of operators was sufficient since the operators cut the same stands with the same harvester with the same bucking and cutting instructions. Six operators enabled the elaboration of these work phases where there is potential to improve the working techniques. Generalization of the productivity, which was not the objective, for a larger number of operators would have necessitated a much wider study arrangement. The study operators cut in two thinning stands and there were no significant differences in

working techniques. A rational reason for this was that the stands were not different enough to change the technique. However, it is not excluded that the working technique would not change in different conditions (e.g. steep slope), which for the working technique, as with the productivity, is dependent on the work environment.

On the other hand, six professional operators are few for the psychological study, which impedes the complete generalization of the results for a larger population. The operators' test results are reliable on an individual level since the tests are standardized and commonly accepted. In addition, the results support previous studies of forwarder and harvester operators' abilities (Lehtonen 1975, Leskinen and Mikkonen 1981, Parisé 2005), therefore, some generalizations can be made. The results also show the connection between schemas, which have been found in previous studies of harvester work (Gellerstedt 1993, Tynkkynen 2001, Ranta et al. 2004, Kariniemi 2006). In the student group, the learning process to become a professional harvester operator is ongoing and, therefore, the results are trend-setting. The group was heterogeneous and the students had differing levels of training, which also lead to unpredictable variations in the results. Testing the students individually, as was done for the operators, would have given more reliable results.

In the work study of the harvester simulator cutting, the results are dependent on the hardware (the structure of a simulator as whole) and the software (visualization programs) as the real harvester work study is also dependent on the used harvester type. For this reason, changes in the hardware and software lead to different kinds of results. It is possible to generalize the results of this study for similar harvester simulators where the hard- and software features are similar.

4.6 Outlook for the future

Since the harvester operator is an irreplaceable part of the harvester work and the importance of the operator in the forming of productivity has increased, in addition to the productivity differences between different harvester marks being small, the potential of the harvester operator will be increasingly utilized in the future. The first and the easiest step required is the improvement of the operator's working technique. After achieving this, the next potential is the operator's mental abilities, which is not the easiest thing to improve. Mental abilities are possible to train in small scale by exercises, but inherit characteristics are difficult to develop. Consequently, the question of student selection by versatile adequacy tests should be accepted.

A part of the operator's mental load originates, by implication, outside the harvester and forest. Productivity of work can be increased, to some extent, through organizational means, which would diminish the operator's mental load and thus speed-up decision making. For example, it is not reasonable to cut all possible wood assortments from all stands when the bucking instructions could include only certain types (e.g. Nurminen et al. 2006). The decreased number of wood assortments would make the work more fluent and increase productivity.

The motivation of the harvester operator to be productive originates externally, typically from salary, or internally through the operator's own interest to develop in the work. The utilization of the operator's potential and even the binding of minimum salary to particular productivity levels necessitated that the operator has a possibility to follow and obtain feedback on their own productivity and thus to improve it. Hence different kinds of automatic feedback systems of productivity and activity are needed. A suitable feedback system is also able to report on which work function the operator has the most potential to improve.

Nowadays, a harvester itself collects a large amount of information about its own and the operator's activities, which enables wide possibilities for research depending on the points of interest. Control commands moving along harvester CAN-buses enable a large number of calculations, so the question is more how the all information could be utilized. In the future, the follow-up of harvester work and operator will improve. In addition, detailed information of the control commands of the harvester enables psychological research of selection and decision making, and their speed.

In this study, the working technique of first thinnings was studied on a rather descriptive level giving information of factors under which the work is performed. The topic could be developed to focus on simulation and optimization of harvester head movement and harvester positioning, when the most optimal method to work would be found. Equally important would be the examination of working technique in second and third commercial thinnings and in clear cutting. In the second and third thinnings the work is performed in the same way as in first thinning, however, the increased stem size and the increased number of wood assortments influence the technique. In clear cutting, the selection order of removable trees is easier than in thinning but by studying the possibilities of minimal-movement working technique it is possible to increase the productivity. In addition, working technique, the influence of edge trees, operator's tacit knowledge and, especially, the optimization of forwarding order of separate wood assortments are relevant topics in the field of forwarder research.

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