Comparison of Harvester Work in Forest and Simulator Environments

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Harvester simulators offer a safe and cost-saving method for studying the basics of harvester controls and working technique. Therefore, harvester simulators are increasingly being used in the education of harvester operators. In this study, the objective was to compare harvester work in real and simulator environments, and to determine how a professional harvester operator's working technique may have changed in the simulator environment. Specific features of the simulator that encumbered operators' normal work are also presented; and the correspondence of the simulator to reality is evaluated. The work of six professional harvester operators was studied in thinning and in clear cutting stands in both environments: first in the real forest and thereafter on the simulator. The results indicate that the operators' working technique on the simulator was mainly the same as in the real forest. This means that the same restrictions are valid on the simulator as in the forest. The basic principles of harvesting must be known so that high productivity and good quality can be obtained. However, certain simulator-specific features encumbered the work of harvester operators. Limited visibility to the side increased the need to reverse and the 3D-visualization caused failed catches. Improvements in software would remove some of the defects, e.g. failed felling and cheating in the felling phase. These results also indicate that simulators can be used for research purposes.

Keywords single-grip harvester, harvester simulator, working technique, time study, PlusCan
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1 Introduction

A modern harvester is complex, expensive, and difficult to operate productively. In some countries to which harvesters are delivered, there is no professional training for this kind of machine (Freedman 1998). Learning-by-doing is a common way to learn how to use harvesters; this can be dangerous, lead to ineffective work methods and thereafter to low productivity. Therefore, much interest is paid to harvester simulators, which offer a safe and cost-saving method for studying the basics of controls, data systems and working techniques. Therefore, harvester simulators are playing an increasingly important role in the education of new harvester operators.

In a broad sense, the harvester simulator creates one kind of virtual reality (VR). VR includes all experiences where the reality is not present. More specific definitions are used to describe particular VR areas, e.g. virtual environment (VE), better (Heim 1993). VE means an almost real environment, which is created in technical ways. The definition of VE is not limited by one way of implementation, but it has to conform to certain characteristics. A user must see in all directions and be able to move, and the system must react to these movements (Kolasinski 1995). The VE should also be autonomous; it cannot predetermine what will happen. It should be deterministic and exact, and it must be based on methodicalness, not on chance. Interaction and everything that happens inside the VE must be controlled by rules. VE should also be immersive, giving the user a feeling of presence in the new environment (Reitmaa et. al. 1995, Uusitalo and Orland 2001). On the basis of these definitions, harvester simulators can be classified as non-immersive virtual environments, because the scene of the ongoing work is projected on the wall (Juola 2001). They give a sense of presence in the environment, but the feeling of total immersion is lacking.

The objective of simulator training is to internalize a work model that is correct and practical in real work (Vartiainen 1985). Transfer describes how well the simulator has managed to fulfill this purpose. Some transfer studies have concluded that no transfer was observed (Kozak et. al. 1993, Kenyon and Afenya 1995). Transfer can also be classified as negative, if the simulator training rehearses incorrect work models, which are incorrect in real work (Juola 2001). In most transfer studies, however, simulator training has been observed to affect the trainees' skills positively (Platon 1995, Standon and Cromby 1995, Rose et. al. 1998), and the general opinion is that controlled simulator training is beneficial.

The effect of harvester simulators on students' skills in handling harvesters has been studied very little. The question of replacing real machine training by simulator training has also been under discussion in many contexts. Freedman (1998) compared a group of students who had trained 25 hours with the simulator to students with no simulator training. The result was that the simulator-trained students cut 15% more wood and the repair costs decreased by 30%. He also used the simulator to identify potential and productive operators. Yates (2000) observed that students who were expected to cut 20 trees/hour during their first weeks in the woods actually started with 40 trees/hour and after a six-week training period they reached an average of 80 trees/hour. Students had completed 30 hours of simulator training prior to training with the real excavator-based harvester. Hoss (2001) replaced the first 10 hours of practical training with simulators and compared these students to those who had started with real machines. He concluded that replacing the early steps of practical education with simulators has no negative effect on the result.

Simulators evidently have a positive effect on productivity and learning. However, training on the simulator and controlling of the exercises have been observed to be difficult. Wiklund (1999) found that the greatest benefit from the simulator training was for those students who felt uncertain about handling a harvester. He also pointed out that the training should be well planned so that the students remain interested. Ranta (2003) has also stated that simulator-based learning of how to handle a forest machine needs a clear plan and a connection to the curriculum. Meaningful themes of the curriculum create an appropriate entity for trainees, teachers, planners and administrators. Educational methods, used with the simulator, play a very important role in the whole simulator training (Regian 1996).

Students' motoric skills for handling a harvester start to develop already during the first contact with the machines. Therefore the simulators play an essential role in creation of the internal model. For this reason, the simulator should be realistic, despite its limitations and the differences from the real harvester. Most of the differences can be pointed out by a teacher, and some of the students will notice these themselves. However, it is not known exactly how well the productivity of the simulator corresponds to that of the real harvester. If professional harvester operators have difficulties in some work phases on the simulator, this reveals the most obvious differences from reality.

The objective of this study was to compare

Table 1. Stand characteristics of the thinning stands and the clear cutting stands in the forest and on the simulator. *All* includes trees over 3 cm at dbh as well as merchantable trees. Average tree height and diameter are calculated on the basis of removed trees.

Environment	Trees/ha, merchantable / all (before cutting)	Trees/ha, merchantable / all (after cutting)	Average height, m	Average dbh, cm	Merchantable trees, totally
Forest					
Thinning A	1232 / 1544	643 / 813	14.6	12.7	1913
Thinning B	1071 / 1587	630 / 985	14.4	13.2	1385
Clear cutting	473	–	19.4	22.1	705
Simulator					
Thinning	1808	not calculated	11.6	18.7	797
Clear cutting	464	–	18.7	29.5	334

harvester work in the forest with simulator environment at each phase of work, and to describe how and where the working technique of operators 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.

2 Material and Methods

2.1 Study Stands in the Forest and on the Harvester Simulator

The study material consisted of work studies carried out in experiments in a real forest and in the virtual harvester simulator environment: first in the real forest and thereafter on the simulator (Table 1) In the forest, harvester operators worked in two different kinds of thinning stands dominated by Scots pine (*Pinus sylvestris*) and in one clear cutting stand dominated by Norway spruce (*Picea abies*). The stands were located in eastern Finland near the municipality of Valtimo. In the simulator environment, the aim was to create the same kind of stands as in the forest.

On the harvester simulator, a generated stand consists of 12.5 × 12.5 m squares. Trees are generated on the squares on the basis of tree height and species, and how many trees are growing there per hectare. The tree height varies a maximum of one metre around the given height. Tree diameter at breast height, 1.3 m (dbh), is calculated on the basis of tree height. Trees are randomly placed on the squares, and the stand generator creates 5 different kinds of squares and utilizes 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. Visualization of the stands must also be similar with the real forest stands.

2.2 Operators and General Settings

In the study stands, the work of six harvester operators was studied. The operators were professionals who had two to 20 years of work experience. Operators 2 and 4 had operated mostly in clear cutting stands, while operators 3 and 6 had operated mostly in thinnings. Operators 1 and 5 had worked equally much in both types of stand. All the operators had experience with many models of Timberjack harvesters, and the one criterion set for the operators was that they were all familiar with the Timbermatic 300 system of control and measurement.

In one stand, one operator operated three experimental areas a day. Each experiment lasted 45 to 60 minutes. During the experiment, the operator could choose freely the place of the strip road, except that the distance between strip roads was set at 20 m according to the general directive. The operator also chose the trees to be removed.

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 (Fig. 1). The hardware elements such as operator chair, controls, and onboard computer were taken from real machines, and the software was programmed accordingly. All the operators cut the same thinning stand twice and the same clear cutting stand once. The second time an operator worked on the thinning stand, the strip road was marked with poles, along which he had to drive. In the first experiment the route for the strip road, chosen by the operator, was almost the same as the marked route. Each simulator experiment lasted 40 minutes.

Harvester work is influenced by many changing environmental factors. For this reason the number of variables that might cause extra variation was limited and the experimental terrain was chosen so that for all operators it would be as flat as possible. To obtain more comparable results, the sites for the experiments were chosen from locations in the stands where the stand structure was as similar as possible for all operators. During the forest experiments, the ground was covered by a 20 cm layer of snow and, in particular, in the clear cutting stand, falling snow from trees limited visibility in the felling phase. On the simulator, the terrain caused no problems for operators or the machine.

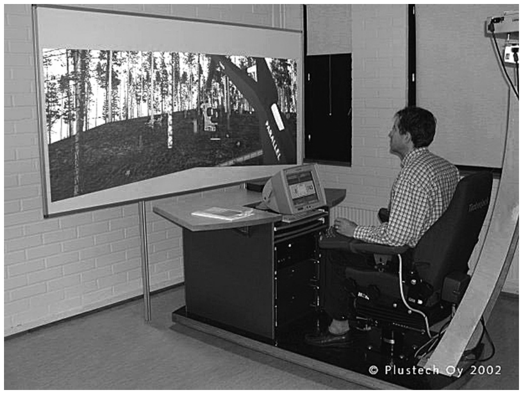

Fig. 1. Timberjack harvester simulator.

2.3 Time Study, Observation of Work Technique and PlusCan Data Logger

Three methods of data collection were used in both the forest and in the simulator stands. One researcher used the hand-held Rufco computer to make the time study and another used the hand-held Psion computer to collect observations of work technique (Table 2). The data in the PlusCan data logger were unpacked after each experiment. The data from the data collection methods were joined into one Excel-sheet as a large matrix.

The harvester operators' work was measured using a time study method where the work was divided into 5 main phases: moving, positioning-to-cut, felling, processing (delimbing, crosscutting and placing), and non-productive time. In this study, the normal work phases were divided into more detailed units.

The moving phase began when the harvester tracks started to move and ended when the harvester stopped to perform some other task. 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 and the felling cut began.

The felling phase started when the felling cut began and ended when the feeding and crosscutting work phase was launched. For this reason, felling was divided into two categories in the thinning: normal felling (moving of a stem less than 3 m from the stump) and felling with moving of a stem over 3 m. In clear cutting, if the operator moved the stem after normal felling or felling with moving by dragging it on the ground, this time was separated from the total felling or felling with moving time.

Processing consisted of delimbing and crosscutting. The processing phase ended when the operator lifted the harvester head to an upright position. When the limbs of the trees were so large that it was difficult to delimb by using feeding rolls only, the harvester head followed the stem and delimbed it while the stem was in the same position. This kind of delimbing time with moving of the harvester head was separated from the total processing time in clear cutting.

Non-productive time consisted of clearing, steering the boom front, piling logs, moving tops and branches, and short delays caused by the operator. Steering the boom front occurred when

Table 2. Time study and observation of work technique.

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	10. Distance to nearest trees on the strip road after moving, m
– Moving tops and branches	
– Delays	

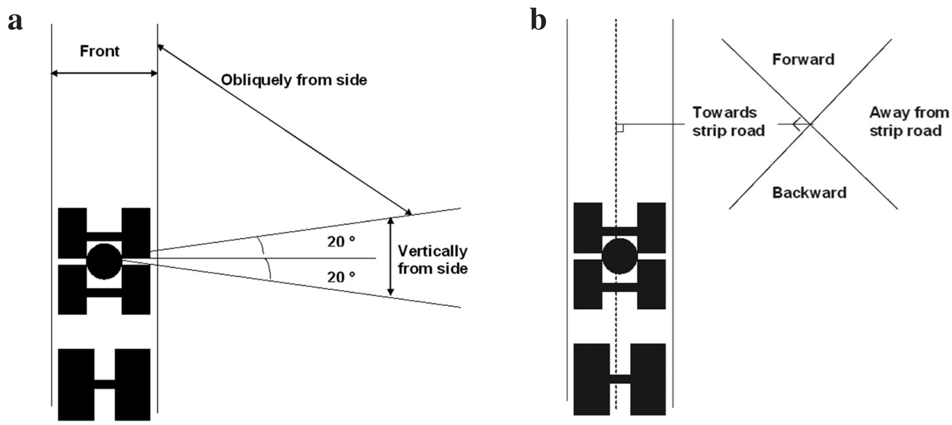

Fig. 2. Pick-up (a) and felling directions (b). The same directions are on the left side too.

the operator steered the harvester head to the front of the machine before the moving phase. Total effective working time included all of the previously listed work phases. Delays and breakdowns caused by the machine or its data system were excluded. All observations of time study focused on one tree at a time.

When the work technique was observed, seven different kinds of observations were recorded for each removed tree: pick-up side (left, right, front), tree species, pick-up direction (Fig. 2a), distance, felling direction (Fig. 2b), processing location and distance to the processing location. Distances of the removed trees, processing locations, boom directions and crane movements were based on visual estimates during handling of the tree. A researcher stood either in front of or behind the harvester. Therefore, all distances were estimated at a vertical angle from the middle line of the strip road. The processing location was divided mainly into two cases: processing beside the strip road and processing at the side of the stand. Moving was observed when the operator drove to a new working location. Moving distance and the distance of the wheels to the nearest trees on the strip road were estimated along the strip road after the moving phase. Moving distances smaller than 0.5 m were not recorded.

Table 3. Average stem sizes and the proportion of tree species in the clear cutting and in thinning in both environments. Averages and standard deviations are calculated on the basis of the operator specific averages and distributions of tree species.

	Average stem sizes, dm^3			Distribution of tree species, % (pine, spruce, birch)		
	Thinning		Clear cutting	Thinning		Clear cutting
	Stand A	Stand B		Stand A	Stand B	
Forest						
Average	85.8	82.6	517.5	56, 4, 40	59, 38, 3	7, 86, 7
St. dev.	13.2	8.3	121.1	8, 3, 9	8, 7, 3	3, 5, 7
Simulator						
Average	106.6		457.0	33, 67, –		14, 79, 7
St. dev.	4.8		10.9	5, 5, –		2, 3, 1

Control units of the harvester communicate with each other through CAN-buses (Controller Area Network). The traffic in the CAN-buses of harvester can be monitored with a PlusCan data logger (manufactured by Plustech Oy, Tampere), which makes possible to obtain very detailed performance times for each work phase. Both in the forest and on the simulator, the device was connected to the system. In this study, Pluscan's data utilized only part of the stem volumes.

The data from the forest thinnings were analyzed in togethet on the basis of similar stand structure and larger number of observations. The data of the simulator thinnings was also analyzed in together, because no differences were observed in operators' functions between the two thinning times.

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 4. Difference on the simulator, based on the number of merchandised trees removed per effective hour for thinning and for clear cutting in both environments.

	Productivity difference on the simulator, %	
Operator	Thinning	Clear cutting
1	35%	144%
2	8%	35%
3	–33%	44%
4	–3%	63%
5	–25%	41%
6	–17%	70%
Average	–6%	66%
Std. dev.	25.1%	40.6%

3 Results

3.1 General

In the forest, the average stem sizes of the thinning stands were almost the same (Table 3). The average stem size was a little larger in simulator thinning and the proportions of tree species was dominated by spruce.

The productivities of operators 1 and 2 increased in the simulator thinning compared to the real forest but the productivities of the other operators decreased (Table 4). In the simulator clear cutting, the productivities of all operators increased.

When productivity is described as a function of stem size, it can be seen that in the thinnings the productivities were very similar; whereas in clear cutting, productivity levels differed by over 40%-units from the real productivity level (Fig. 3).

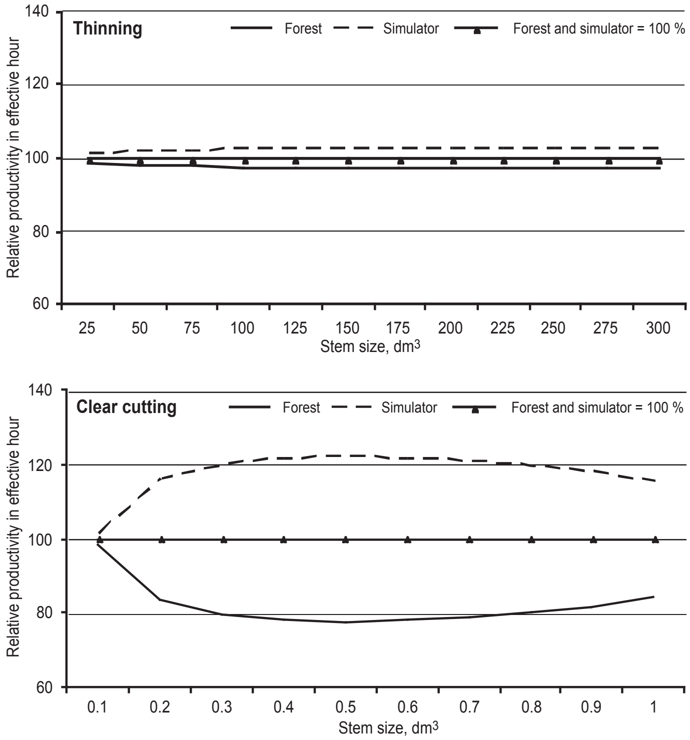

Fig. 3. Relative productivity curves from the thinnings (a) and the clear cutting (b). The curves are calculated for the total data from both environments and compared to the average productivities by each volume class.

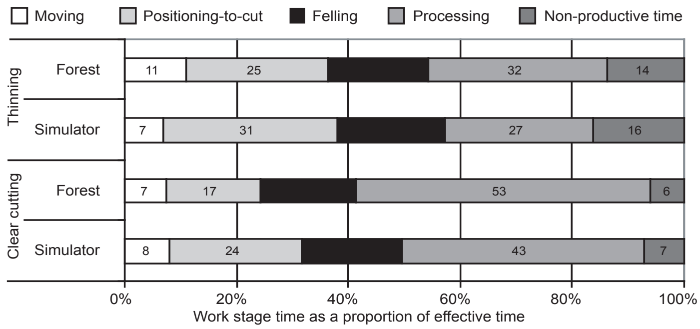

Fig. 4. Structure of effective work time divided by main work phases in each environment.

The time structure of effective work as a proportion of effective time was mainly the same in both environments (Fig. 4). In both stand types, the largest differences were in positioning-to-cut and processing phases. The proportions of times in various phases varied between thinning and clear cutting.

3.2 Moving

On the simulator, the driving forward percentage was smaller than in the forest (Table 5). In both thinning and clear cutting stands, the difference in average driving distance, which was smaller on the simulator than in the forest, was

Table 5. Differences in moving work phase in the forest and in the simulator environment. The Wilcoxon's test verified the statistical significance.

Operator	Driving forward percent of total driving time		Average driving distance, m		Trees removed in one working location		Speed, meters/minute	
	Forest	Simulator	Forest	Simulator	Forest	Simulator	Forest	Simulator
Thinning								
1	82.5	82.3	3.5	2.2	3.5	4.7	12.7	17.8
2	81.1	91.2	3.3	2.7	3.3	3.5	11.3	14.9
3	86.9	71.3	4.1	1.9	3.8	3.4	17.5	9.7
4	89.3	80.7	4.1	2.7	3.3	3.1	17.7	17.4
5	93.3	83.8	3.6	2.0	3.5	4.2	21.5	17.2
6	86.5	75.1	3.5	2.1	3.3	2.9	20.0	13.8
Average	86.6	80.7	3.7	2.3	3.4	3.7	16.8	15.1
p-value	0.173		0.027		0.673		0.345	
Clear cutting								
1	81.1	92.1	6.3	3.9	2.5	2.6	18.1	39.5
2	86.2	86.8	4.9	2.8	4.3	2.5	20.9	15.2
3	85.8	83.1	5.8	3.2	2.5	3.1	22.3	11.1
4	95.1	91.3	5.0	3.2	2.8	2.8	31.2	25.6
5	88.4	91.7	5.0	2.8	2.6	1.9	25.6	26.4
6	87.8	83.1	5.9	4.8	2.8	3.8	31.5	22.8
Average	87.4	88.0	5.5	3.4	2.9	2.8	24.9	23.4
p-value	0.917		0.028		0.893		0.463	

Table 6. Operators' average positioning-to-cut times and positioning-to-cut distances. The Wilcoxon's test verified the statistical significance.

Operator	Thinning				Clear cutting			
	Average positioning-to-cut distance, m		Average positioning-to-cut time, s		Average positioning-to-cut distance, m		Average positioning-to-cut time, s	
	Forest	Simulator	Forest	Simulator	Forest	Simulator	Forest	Simulator
1	4.0	3.3	9.2	8.2	5.5	4.3	9.8	7.8
2	4.3	2.9	9.6	11.5	5.1	4.7	13.1	11.2
3	4.0	2.7	7.3	15.5	5.1	4.6	11.5	12.3
4	4.0	3.1	10.5	11.8	4.8	4.4	11.2	11.3
5	3.7	3.5	7.5	9.6	5.4	5.0	8.4	10.7
6	4.4	2.9	10.3	14.4	5.3	4.4	12.0	10.1
Average	4.1	3.1	8.9	11.3	5.2	4.6	10.9	10.4
p-value	0.028		0.046		0.026		0.752	

statistically significant. However, the number of trees removed at one work location was only 9% greater in thinning. On the simulator, the number of trees per hectare was larger, and the operators could thus remove more trees from one working location. Driving speeds were about the same in both environments.

3.3 Positioning-to-cut

Positioning-to-cut required more time in simulator thinning than in forest thinning (Table 6). The average positioning-to-cut distance was, however, shorter in simulator thinning and clear cutting compared to the real forest. Positioning-to-cut distance is a vertical distance from the last working place or from the middle line of the strip road to the next removable tree depending on the last work phase. In clear cutting, the average posi-

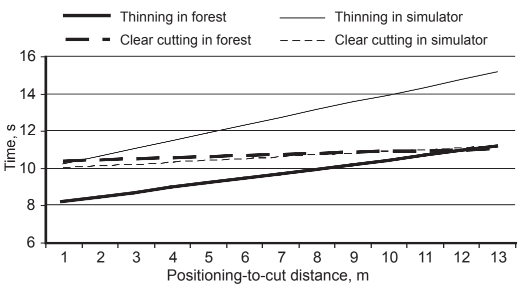

Fig. 5. Effect of the positioning-to-cut distance to positioning-to-cut time.

tioning-to-cut times were almost the same. All the variables, except average positioning-to-cut time in the clear cuttings, differed statistically significantly.

Dispersion of positioning-to-cut times 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. Furthermore, in both environments all the operators' dispersions were large. 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 (Fig. 5).

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 (see Fig. 2a). The proportions were the same in the clear cuttings, and less than 10% of the trees were removed vertically from the side.

3.4 Felling

Felling with over 3 m moving took about 2 seconds more than pure felling in thinnings (Fig. 6a). 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. Trees that were located far from the strip road had to be moved closer to the strip road. The difference between simulator felling and forest felling times with different methods was less than 2 seconds. The lines of felling without moving differed significantly between the environments (p = 0.01)

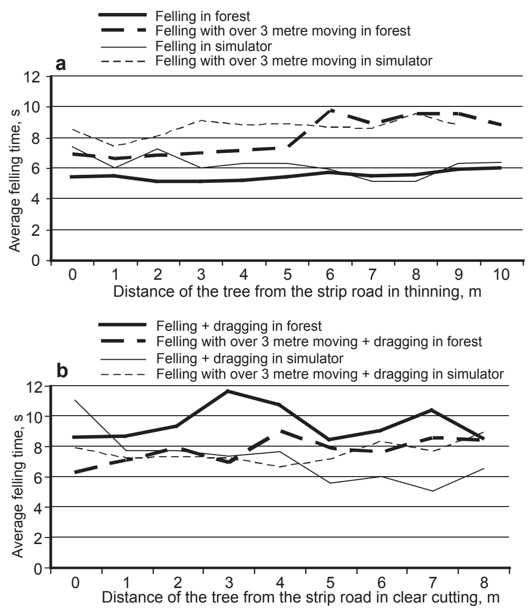

Fig. 6. Effect of distance of the tree to felling time with different felling methods in thinning (a) and in clear cutting (b).

In clear cuttings, felling with over 3 m moving + dragging took roughly 2 seconds less than felling + dragging in the forest because with the first technique the dragging distance was smaller (Fig. 6b). During felling, and especially before the crown hit the ground, the tree is light to move in the air. On the simulator, the dragging phase happened too fast. The felling + dragging lines differed significantly between the environments (p = 0.028).

In thinnings, operators 3 and 5 avoided moving trees over the strip road in the forest, which would have increased the time consumed in the felling phase. They processed trees close to the stump so that the distances the trees had to be moved were short (Table 7). In the simulator environment, those operators used the same technique. The differences between the forest and the simulator environments in the proportion of trees moved over the strip road and in the average moving distance were not statistically significant.

In both types of stands the proportions of felling directions for different distances in the forest followed the felling directions on the simulator

Table 7. Percentage of trees moved over the strip road and the average moving distance of tree from stump to processing location. The Wilcoxon's test verified the statistical significance.

Operator	Trees moved over the strip road, %		Average moving distance of tree from stump to processing location, m	
	Forest	Simulator	Forest	Simulator
Thinning				
1	34.3	22.9	3.9	2.8
2	28.1	34.4	3.5	3.2
3	9.6	8.3	1.8	1.9
4	14.8	22.1	2.3	2.4
5	12.5	7.9	2.0	2.0
6	31.6	22.3	3.5	2.1
Average	20.4	19.4	2.7	2.4
p-value	0.463		0.223	
Clear cutting				
1	52.1	40.5	6.6	5.2
2	37.1	36.0	5.0	5.2
3	22.7	34.1	4.5	4.6
4	38.7	25.4	5.1	4.1
5	48.6	37.9	5.9	5.2
6	50.0	36.7	6.0	4.3
Average	41.6	35.3	5.5	4.8
p-value	0.115		0.116	

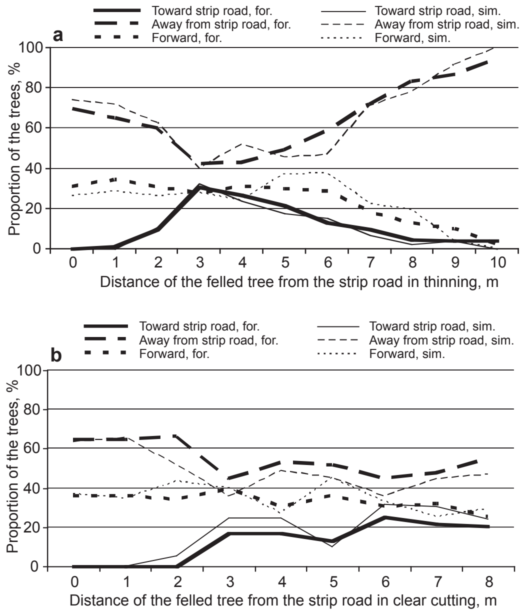

Fig. 7. Proportions of felling directions in different distances in thinning (a) and in clear cutting (b) in both environments.

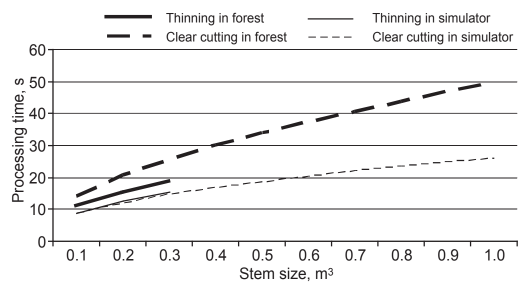

Fig. 8. Differences in processing times as a function of stem size on the simulator and in the real forest.

(Fig. 7). 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 the thinnings, felling direction proportion-lines did not differ statistically between environments. In the clear cutting, only forward felling directions corresponded to each other statistically sufficiently in Wilcoxon's test ($p = 0.374$).

3.5 Processing

The processing work phase (delimbing, crosscutting and placing) generally took less time on the simulator than in the forest (Fig. 8). In thinning, the difference between the environments was not large, but in the clear cutting the difference was considerable, about 20 seconds. When real forest stands are compared, the processing time for the same size clear cutting tree differed from a corresponding thinning tree.

In thinning, the most popular processing location was on the left side beside the strip road where 42.2% of the trees were processed (Fig. 9). The percentage of trees processed at the side of the stand depended on the operator and varied from 15 to 50%. A productive operator could utilize all the processing places equally well. In clear cutting, trees were almost completely processed

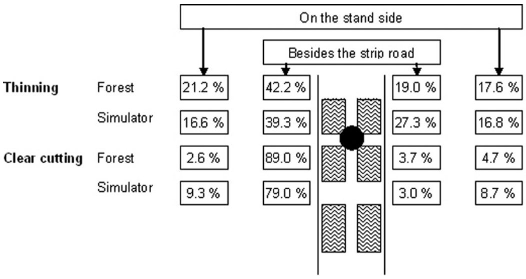

Fig. 9. Distribution of processing locations related to harvester.

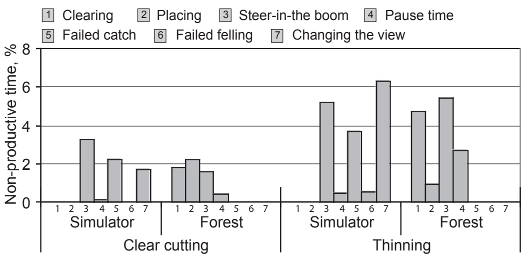

Fig. 10. Non-productive time divided into detailed units in the forest and in the simulator environment.

on the left side beside the strip road. However, on the simulator, the distribution of trees processed on the stand side was larger.

3.6 Non-productive Time

In the total series, the proportion of non-productive time of the total effective time was larger in the thinnigs than in the clear cuttings (Fig. 10). On the simulator, the tops or logs of a processed stem could not be picked up and moved after the stem was cut. There were also no trees to be cleared. Failed catches occurred when the operator could not get the harvester head to the butt of a certain tree and instead steered the harvester head to some other tree. If during the simulation the operator released the harvester head from the butt of the tree during felling, the tree might disappear totally. This kind of simulator-based felling failed several times.

4 Discussion

In this paper harvester work was compared by creating similar thinning and clear cutting stands in a simulator environment as in the forest. Methods of data collection, collectors and devices were the same in both environments. A time study, combined with observation of work technique and PlusCan data, enabled a comparison of time units to distances and tree volumes, which enabled an analysis of different kinds of working techniques. The environments were compared according to work phases and operators; and, when feasible, the differences were analyzed statistically. Operators were also motivated to operate with the simulator harvester. Therefore, these results should be valid and reliable.

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 from 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. In this sense, the simulator creates the environment similar to the reality and enables meaningful training.

A characteristic specific to the simulator was that, when the operator viewed the simulator thinning, inactivated trees appeared to be small in size and the forest looked sparse. Therefore, the number of stems per hectare was higher as in the real forest that the visualization would be similar with the real forest. A tree was activated when the machine or the harvester head reached it. This disturbed tree selection. The tree shape also narrowed quickly (see Table 1). Shorter trees speeded processing a little although the volumes of the trees were almost the same. Visualization of the clear cutting stand corresponded well with the forest stand.

On the simulator, speed, acceleration and steering worked like in a real machine. Gradients were also modelled but rolling over of the harvester was not possible. Roughness of the ground and stumps could not be sensed as swinging of the cabin. If the machine faced even a small tree, it stopped moving. The driving forward percentage of the total driving time was smaller in the simulator thinning. 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.

On the simulator, operators had difficulties to discern the stereoscopic effect of the simulated forest, which caused failed catches and increased the positioning-to-cut time, especially in thinning. Ranta (2003) and Laamanen (2004) made the same observation. 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. However, the positioning-to-cut distance affected the time consumption in similar way in both environments.

On the simulator, the delimbing knives did not need to be tightly closed around the tree butt for the felling cut to be launched. Operator 3 had difficulties in grabbing because he tried to imitate the technique with the real harvester. The harvester head also caught the felling tree automatically in the air. Operator 1, in particular, took advantage of this characteristic, which speeded up his felling. If the harvester operator is not aware of this fault on the simulator, cheating in the felling phase can lead to a wrong, even dangerous, work model.

In clear cuttings, removed stems are generally larger than in thinnings. In the simulator clear cutting, the dragging phase took less time than in the real forest. Dragging of the tree on the ground takes more time and power when the mass to be dragged is large. A fault in the dynamic force effects in the boom and stems moved trees of different sizes at the same speed on the ground and through the harvester head.

Processing, and especially feeding, happened too fast for larger stems and caused higher productivity in simulator clear cutting. This can be explained as being due to the above-mentioned reason and also 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 bucking file. 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.

On 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 units than in the reality. Improvements in software would remove some of the defects, e.g. failed felling.

The simulator work was projected on a wall. The normal view from the cabin of the harvester simulator was forwards and quite limited. Operators willingly removed those trees that could be removed without any extra functions and which were located in the visual range. Head-mounted display or extra projectors to project the sides onto side walls would increase the feeling of immersion.

These results also indicate that simulators can be used for research purposes when differences from reality are controlled. The number of changing variables is limited, and certain aspects of the harvester work can be separated for more detailed study. The variation in forest heterogeneity can be minimized and thereby standardized to similar forest circumstances.

To sum up, the harvester simulator has all the main elements and restrictions set by the real forest, under which the real harvester work must be performed in the real forest. For example, in thinning, the remaining trees set a limit for the operator. Therefore the basic principles of harvesting must be known so that high productivity and good quality can be obtained. Steering the crane and driving the harvester were the most realistic phases. However, some improvements (in felling, defects in stems, dynamic force effects, and 3-D visualization) in the software of the simulator would make it an even more practical tool for learning the basics of harvester work. On the simulator, the operator learns and uses those tricks that benefit simulator cutting. Simulator training combined with forest training will improve the education of harvester operators.

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Total of 19 references