Cutting Corners with a New Crane Concept

Ola Lindroos[1], Dan Bergström[1], Petter Johansson[2] and Tomas Nordfjell[1]

[1]Dept of Forest Resource Management, Swedish University of Agricultural Sciences, Sweden

[2] Sveaskog, Box 71, SE-921 22 Lycksele; Sweden

Published 2008 in *International Journal of Forest Engineering* 19(2), 21-28.

Abstract

It is only possible to pivot (horizontally rotate) conventional harvester cranes at the crane pillar. A new type of harvester crane has an extra pivoting point on the outer boom, which makes it possible to reach behind residual trees and thus probably ease thinning work. This paper quantifies differences in harvester time consumption between a conventional crane and a pivoting outer boom (POB) crane in thinning by the use of a simulation study and a field study. Simulations were made in two mapped stands. A harvester equipped with a POB crane was used in the field study. The work of a conventional crane was performed with the same machine by not using the pivoting function. Six blocks were created with densities ranging from 1230 to 3100 trees per hectare and the tree choice was restricted.

The POB crane required 4-8% less time compared to the conventional crane in the simulation study and 7-15% less in the field study. In the field study, the POB crane's mean time consumption was significantly lower for the work elements *machine movement backwards* and *crane out*. The number of machine movements backward was significantly lower for the POB crane, and 17% more trees could be cut per machine position by the POB crane. The pivoting function was used on 29% of the cut trees. Based on the consistent results from the simulation and the field study, it is concluded that the pivoting function significantly increased productivity in thinning.

Keywords: machine development, comparative time study, simulation, time consumption, productivity, thinning, CTL, harvester.

Introduction

To conduct thinning operations with a harvester according the cut-to-length system is demanding for the operator (Gellerstedt 1993, Nåbo 1990). Up to 200 trees per hour are felled, delimbed, cross-cut and piled while the remaining 1000 – 1500 trees per hectare are to be left undamaged (c.f. Nurminen et al. 2006, Sirén and Aaltio 2003, Talbot et al. 2003). Over the years, a combination of technical machine improvements and improved work methods has increased the harvesting productivity in this difficult operation (c.f. Fryk et al. 1991, Nurminen et al. 2006).

One important component of a harvester is the crane. In this paper, the term crane refers to the system of hydraulic cylinders and mechanical levers (Gerasimov and Siounev 2000) (i.e crane pillar, mid boom, outer boom and extending boom). In some other texts, boom is used as a synonym for crane but here it is avoided in order to not confuse the system with its components. One of the limiting factors for thinning productivity is the work to reach trees selected for removal without damaging residual trees. Since it is only possible to pivot (horizontally rotate) most harvester cranes at the crane pillar, a tree has to be reached with a linear movement of the harvester head up to a distance of 11 m from the crane pillar. To avoid damage on residual trees the crane movements generally have to be slow (Bergström et al. 2007) and to reach trees, the machine often has to be repositioned short distances on the strip road. The repositioning also often includes short reversing movements, depending on difficulties in reaching a specific tree (Eliasson 1999). Reversing is generally associated with decreased productivity (Ovaskainen et al. 2004). A technical improvement that could reduce these problems is a crane that allows a nonlinear movement of the harvester head. In theory, more trees selected for removal could be reached from a given machine position and the speed of the crane could be higher since the distance to residual trees could be increased. A new harvester crane concept developed by the company Cranab AB in Vindeln, Sweden, partly allows such a nonlinear harvester head movement. Cranab's crane has an extra pivoting function located close to the middle of the crane, at the beginning of the outer boom (**Fig. 1**). The same technical feature, but with another functional design, has in the past been used on backhoe loaders to enable ditches being made parallel to the road the backhoe loader is driven on (Gustafsson 1979).

In this paper, the differences in harvester time consumption between a conventional crane and a pivoting outer boom (POB) crane in thinning are quantified. Common methods to determine time consumption for forest machines are time studies (Nakagawa et al. 2007, Nurminen et al. 2006) and simulations (Bergström et al. 2007, Eliasson 1999, Gerasimov and Siounev 1997). In this paper both methodologies are used combining a simulation study conducted before the first POB crane was built with a field time study of a POB crane prototype.

MATERIAL AND METHODS

Simulation Study

Data on two first thinning stands (No. 203 and 602) from Bredberg (1972) were used (**Table 1**), and the tree volumes were adjusted to volume under bark through a 5% reduction of the total volumes. The two stands were chosen to represent the outer extremes in Swedish forests managed for round-wood production, in terms of stand density and standing volume. The position of the trees was identified using Cartesian coordinates. The stands were 40 × 25 m (0.1 hectare), of which 40 × 22 m was used for the simulation. A 3.5-m-wide strip road was located in the center of the stands. The harvester's maximum crane reach was set to 11 m, with a maximum rotation of 110° at the crane pillar to each side of the driving direction. The crane's operational area was limited by a transect perpendicular to the driving direction and crossing it at 8.3 m in front of the crane pillar. The restriction was imposed to avoid unnecessary crane movements, which is important in operational harvesting (Eliasson 1999). For the POB crane simulation, the crane could be pivoted ±30° at 7.5 m from the crane pillar. The simulated starting point for the harvester was 5 m outside the stand and for each machine movement, the maximum distance was set to 5 m. Within the possible distance, the position that allowed reaching the maximum number of trees predetermined for selective thinning was chosen (i.e. the number of trees harvested in the strip road was not considered in the positioning decision). No machine movements backwards were needed in the simulation.

Two intensities of thinning (35% and 50% of the trees removed) were performed for each combination of stand and crane type. The priority stated by Bredberg (1972) for the removal of trees was used. The trees removed in the strip road constituted 74.5% and 57.5% of the total number of removed trees in the sparse stand with thinning intensity 35% and 50%, respectively. In the dense stand, the equivalent shares of trees removed in the strip road were 76.1% and 58.4%.

Time consumption for individual work elements was considered equal for the two crane types; hence, time for machine movements constituted the only time consumption variable analyzed. The time taken for machine movements (T_{MOVE}, s ha^{-1}) was calculated according to Equation [**1**] (Eliasson 1999).

$$T_{MOVE} = (C \times N + \sum S / v) \qquad [\mathbf{1}]$$

Where
C = time required for preparing the machine to move (s)
N = number of machines positions (n ha^{-1})
S = distance between machine positions (m)
v = machine's speed (m s^{-1})

Based on values provided by Eliasson (1998), C was set to 5 seconds and v was set to 1 m s^{-1}. The machine repositioning time in a stand was set to 25% of the total time for the thinning operation, based on values supplied by Lagesson (1997). Consequently, machine repositioning time was multiplied by four in order to obtain total time for the tinning operation. The simulation was conducted in December 2005.

Field Study

The study was performed in a pine (Pinus sylvestris) dominated stand (> 97% of the standing volume) in Västerbotten county in Northern Sweden. Within the stand, 12 treatment units with a size of 50 × 20 m (0.1 hectare) were created. All trees were within the harvester's operational reach from the strip road, which was located in the center of the treatment units. Strip road width was 4 m. All area dependent values were transformed to values per hectare. Based on stand density, number and mean diameter of trees selected for removal, treatment units were paired into six blocks to enable comparable replications of the treatments (**Table 2**). The blocking of treatment units was statistically tested by means of paired t-tests, which showed no significant differences within the blocks based on stand density, number of harvested trees or mean tree diameter ($p \geq 0.108$). Block 3 was previously thinned, while other blocks not had been thinned. Blocks 4 and 5 were located on flat ground, while the strip roads in Blocks 1 and 3 were located on the top of a ridge with sloping ground on each side of the road. In Block 2, the strip road sloped 25% uphill and was on even ground for the conventional crane (C) and POB treatment units, respectively. In Block 6, the C strip road sloped 31% uphill, while the POB strip road sloped 30% downhill.

All trees were numbered and their diameter at breast height (1.3 m) as well as stem damage were recorded prior to the study. Within each unit, the trees were ordered in 2-cm-diameter classes and in each class the tree closest to the lower limit was sampled for height measurements. This methodology resulted in circa 10 randomly chosen and height-measured trees for each treatment unit. Based on Brandel's smaller volume function (Brandel 1990), the height and diameters of all sampled trees, breast height diameter based volume functions were created for pine, spruce (*Picea abies*) and birch (*Betula ssp.*) (Equations [**2**] through [**4**]). The functions were used to calculate tree volumes for the study. The volume unit used was m^3 solid stem wood under bark with the stump excluded (m^3 u.b.).

$$V_P = 0.000125 \times D^{2.469998} \qquad [2]$$

$$V_S = 0.000049 \times D^{2.769985} \qquad [3]$$

$$V_B = 0.000097 \times D^{2.500014} \qquad [4]$$

Where:
V = stem volume under bark (m^3 u.b.).
Subscripts P, S and B = pine, spruce and birch, respectively.
D = stem diameter at breast height (1.3 m) on bark (cm).

The two treatments tested in the study were thinning by use of POB crane and by conventional crane. The single-grip harvester used in the study was a Valmet 911.3, which has a total mass of circa 17 tonnes and the crane and cabin on the same rotating plate. The harvester was equipped with a Valmet 350 harvesting head and an 11-m reach POB crane prototype, based on Cranab's parallel harvester crane HC 185. The work of a conventional crane was performed with the same machine, but by not using the crane's POB function. The operator was a 26-year-old man who had been operating harvesters for four years, of which seven months was with the POB crane. The operator's tree choice was restricted to pre-marked trees, both in regard to thinning and to strip road creation. Tree selection was based on spatial distribution, quality and a thinning from below (i.e. prioritizing removal of small trees). Additional trees were allowed to be harvested only if it was required for the machine to fit in the strip road.

The time study was performed in July 2006 in daylight conditions, with an air temperature of +20°C and with no precipitation or wind. Time consumption for the work was recorded through continuous time studies by the use of a Husky FS3 hand-held computer running Siwork 3 version 1.1 software (Kofman 1995). Eight work elements were used (**Table 3**) and if more than one work element were performed simultaneously, the element with the highest priority was recorded. Time consumption was recorded in centi-minutes (cmin) and the total study time was 6 hours and 4 minutes, of which 0.2% was delay time. Although delay time was recorded, it was not included in the analysis since the study focused on main work time (IUFRO WP 3.04.02 1995) which corresponds approximately to the E_0 time. The harvested tree's number was recorded for each work cycle and for the POB crane, use of the POB function was recorded distributed on pivoting direction (left or right). After thinning, the number of log piles and residual trees with stem damages were recorded. A pile was defined as being one or more logs that presumably could be gripped by a forwarder grapple without rearranging logs or damaging residual trees. Hence, the logs in a given pile were not necessarily oriented parallel to each other. A tree was considered damaged if the stem's bark was removed on a total area of 9 cm^2, irrespective of the number of separate damages.

Statistical Analyses

For the simulation study, the number and time consumption at stand level for machine reposition was calculated for each combination of crane type, stand and thinning intensity. Proportional difference in time consumption between crane types was also calculated, both for the machine repositioning time and for the total thinning time. Additionally, mean positioning length and number of harvested trees per machine position were calculated, and the differences between crane types were analyzed by the use of two-sample t-tests.

The field study's randomized factorial block design with two treatments (i.e. cranes types) and fixed block effects was analyzed through analysis of variance (ANOVA) and analysis of covariance (ANCOVA). A general linear model (GLM) was used to analyze the ANOVA and ANCOVA models (Minitab 14, Minitab Ltd.). In the models, covariates were used when they were considered logical and not risked to be confounded with treatment effects. If covariates significantly contributed to the model, least square means were calculated. Work efficiency was analyzed as time consumption per harvested m^3 u.b. while number of machine movements and log piles were analyzed per hectare. Number of harvested trees per machine position was calculated as the quotient of harvested trees and machine positions. The share of damaged trees was calculated as the quotient of damaged residual trees and the total number of residual trees. The critical significance level was set to 5%.

RESULTS

Simulation study

The number of machine positions was dependent on stand density and thinning intensity for the conventional crane, whereas number of positions with POB crane was independent of those variables. Consequently, the mean repositioning distance was longer with POB crane than for the conventional crane and the POB crane's mean reposition distance was independent of stand density and thinning intensity (**Table 4**). Moreover, the number of harvested trees per machine position was higher with POB crane than with the conventional crane, with the largest differences in the highest thinning intensity (Table 4). Compared to the conventional crane, POB crane had lower time consumption for machine movements for all combinations of stand densities and thinning intensities. The largest proportional time saving was found when the dense stand was thinned with the intensity 35% of the tree numbers, for which the POB crane required 8% less time for the whole thinning operation compared to the conventional crane (Table 4).

Field Study

The mean time consumption per thinned m^3 u.b. at a mean harvested stem volume of 0.039 m^3 u.b. was significantly lower with POB crane compared to conventional crane (p = 0.002) (**Table 5**). Crane types differed significantly for the work elements *machine movement backwards* and *crane out* (**Table 5**). Time required for the work elements *waiting* and *felling and processing* was shorter with POB crane than with conventional crane, but the differences were just outside the significance limit (p=0.062 and 0.066, respectively). The time consumption was significantly influenced by mean tree size (**Fig. 2**), with a hyperbolic pattern. Consequently, the reciprocal of the mean tree volume of harvested trees (V^{-1}) significantly contributed to the analyses for the total work time and to the model for three out of seven work elements (**Table 5**). Compared to V^{-1}, the plain mean tree volume and its square, alone or combined, did not improve the model additionally, except for work element *machine movement forward* for which the plain value of mean tree value had a lower p-value (0.017) and a higher R^2-value (69.7%). Other covariates tested were stand density, number of trees harvested, thinning intensity (percent of volume and percent of trees) and mean diameter of harvested trees, of which none contributed significantly to the model of the total time ($p \geq$ 0.075) and no covariate improved the models for work elements more than mean tree volume. Hence, the reciprocal of mean tree volume alone was used when creating a predictive model (Eq. [**5**]) based on the ANCOVA results, to establish a relation between mean tree diameter and the total time consumption per m^3 u.b.

$$T = 332.4 + 25.486 / V - 99.7 \times POB \qquad [\mathbf{5}]$$

where:
T = total time consumption (cmin) per harvested m^3 u.b.
V = harvested mean tree size in m^3 u.b.
POB = dummy variable which gets value 1 if POB crane is used and 0 if conventional crane is used.

Due to the dummy variable in the model (Eq. [**5**]), the POB crane is 99.7 cmin faster per m^3 u.b. than the conventional crane irrespective of mean stem volume. Additionally, the model's feature indicates that the relative difference in time consumption increased with increased mean tree volume. With a mean tree volume of 0.024 and 0.075 m^3 u.b. the POB crane is 7.2 and 14.8% faster, respectively, compared to the conventional crane.

The POB crane's pivot function was used on 29.2% (SD 8.0) of the harvested trees, with no significant difference between pivoting to the right or to the left (p = 0.915).

When using POB crane, the mean number of machine movements backward was significantly fewer than when using the conventional crane (**Table 6**). The mean number of machine movements forward per hectare was not significantly different between crane types. None of the logical co-variates stand density, number of trees harvested or thinning intensity (percent of trees) contributed significantly to the model ($p \geq 0.081$).

The number of harvested trees per machine position was significantly higher when using POB crane than when using the conventional crane (**Table 6**). Using thinning intensity (percent of the volume) as a covariate significantly improved the model and increased the adjusted R^2-value from 84.9% to 99.9% with all factors significant (p = 0.000). The adjusted mean values were 3.4 trees per position for POB and 2.9 for conventional crane, with a mean difference within blocks of 0.50 trees per position (standard error = 0.02).

The number of log piles per hectare did not differ between POB and conventional crane (**Table 6**). The mean number of piles for the six replicates was 286.7 per hectare for POB and 300.0 for conventional crane, with a mean difference within blocks of 13.3 piles per hectare (SD 27.3).

The ratios of trees with stem damage did not differ between POB and conventional crane (**Table 6**). Their mean ratios for the six replicates was 6.8% for POB and 7.9% for conventional crane, with a mean difference within blocks of 1.1% (SD 2.8).

DISCUSSION

In the comparative field study, as many of the influencing factors as possible were kept constant. The machine influence was controlled by using the same machine, with the POB function not used when a conventional crane was studied. Stand influences were handled by blocked repetitions, in which the crane types were randomly assigned to the two study units within a block. Besides machine and stand effects, the influence of machine operator is always crucial in comparative time studies and especially when using few operators. In this case, the study's operator had 3.5 years of experience with an ordinary harvester, and 7 months of experience with the POB crane. Given the small trees (0.025 – 0.079 m^3 u.b.) harvested in the field study, the observed productivity tallied reasonably with other contemporary cut-to-length productivity studies of similar thinnings (Nakagawa et al. 2007, Nurminen et al. 2006, Sirén and Aaltio 2003) and thus indicate that the operator was fully professional. The time consumption found at a mean tree volume of 0.039 m^3 u.b. implies a productivity of 6.8 and 6.1 m^3 u.b. per effective hour (i.e. 175 and 157 trees per effective hour) for POB crane and conventional crane, respectively.

Although the operator's performance can be validated by other studies, the psychological effect on the operator could not be controlled. It is possible that the positive attention given by the crane designers and the researchers before and during the study affected the study's single operator. Additionally, the operator's experience with the POB crane prior to the study could have habituated new work methods that influenced work with a conventional crane in a negative way. Moreover, even though the experimental design aimed at comparing equivalent study units, inherent differences in stand conditions (e.g. tree size, stand density and terrain slope) remained and might have influenced the results. It was therefore appropriate that the field study was combined with a theoretical simulation, in which the variable and empirical field conditions could be matched against the static and assumption-based theory and vice versa. Consistently, both study methods found a lower time consumption when using the POB crane. The difference between crane types was higher in the field study than in the simulation study, which could indicate a small psychological effect on the operator. However, there were also other plausible explanations.

The distance from the crane pillar to the pivoting point on the outer boom was 2.8 m shorter in the simulation compared to the crane in the field study. This was because the simulation was conducted before the first POB crane was built. An additional difference was the simulation's assumption that only the work element *machine movement* was influenced by the crane type used. The field study indicated, however, that also other work elements might be positively influenced in the use of POB crane. Despite the differences, both studies resulted in favor of the POB crane and with time consumption decreases of almost the same magnitude. The combined results clearly indicate a higher productivity when using a POB crane in thinnings.

The increase in numbers of trees reached at a machine position was higher in the simulation than in the field study. Most likely, the reason was that the operator could not utilize the POB crane's potential to the same extent as was possible in the simulations. This was expected since the operator did not include optimization in deciding machine positioning due to time restraints and lack of spatial overview compared to the simulation. Additionally, the operator was restrained to harvesting marked trees and stated after the study that in some cases he would have selected other trees. The pre-determined tree choice in combination with the small lower area limit for damage can explain that the level of damaged residual trees in both POB and conventional thinning were higher than the Swedish recommendations (<5% residual trees with damages ≥15 cm^2 (Bräcke 1998)). However, the found damages were modest compared to many other studies (Vasiliauskas 2001). Moreover, the operator's statement indicated that an adaptation to each crane type's limitation in reach can be expected with a free tree choice. Hence, with the operator choosing trees that easily can be harvested with the given crane type, productivity differences between the two crane types are likely to decrease. On the other hand, the POB crane's reach and productivity advantage are likely to enable thinnings that result in residual stands with higher quality at similar productivity levels as thinning with conventional cranes. However, this argumentation needs to be proven empirically.

In the cut-to-length system, thinning has the highest mental work load (Gellerstedt 1993, Nåbo 1990). An extra crane function could increase the work load further, but the field study's operator denied any such experience. The operator's statement is supported by the increased number of harvested trees per machine position and the decrease in machine reversing, which both suggest possibilities for better work planning and thus a higher level of control for the operator.

The POB crane's extra mass of 175 kg theoretically decreased the lifting capacity by 85 kg at full reach. This could limit the usage of heavy harvesting heads, but at least the 925 kg head in the current study was successfully used at full reach. However, since the same crane was used for both crane types, the potential difference due to a conventional crane's larger lifting capacity was not captured in the current field study.

Gerasimov and Siounev (1997, 1998, 2000) state that it is efficient to design specific cranes for different forest machines. The present paper supports that statement and indicates also that it is efficient to have different crane designs for clear cuttings and thinnings. The POB function was most advantageous in the simulation's dense stand, which is logical due to an increased need to avoid residual trees. In line with this finding, it is assumed that the need to reach in between and behind residual trees in a thinning makes use of a POB function in a way that cannot be found in clear cuttings. On the other hand, when using selective or partially geometrical harvesting patterns in bio-energy harvesting of dense (3000 – 5000 trees per hectare), young stands (c.f. Bergström et al. 2007, Kärhä et al. 2005), the POB crane's capacity of nonlinear harvester head movements would be highly appealing.

The current study also concluded that combining field studies with theoretical simulations is a fruitful methodological approach, in terms of establishing thorough results with limited effort. Further research on the POB crane's efficiency is recommended, mainly on the effect of free tree choice, thinning of larger trees and stands with limited visibility. The crane type's dependency on placement in relation to the cabin is also of interest for further investigations.

LITERATURE CITED

Bergström, D., Bergsten, U., Nordfjell, T. and Lundmark, T. 2007. Simulation of thinning systems and their time requirements for young forests. Silva Fennica 41(1), 137-147.

Brandel, G. 1990. Volymfunktioner för enskilda träd: tall, gran och björk [Volume functions for individual trees: Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula & Betula pubescens)]. Report 26. Department of Forest Yield, Swedish University of Agricultural Sciences. Garpenberg.

Bredberg, C.-J. 1972. Type stands for the first thinning. Research Notes 55. Department of Operational Efficiency, Royal College of Forestry. Stockholm.

Bräcke, J. 1998. Gallringsundersökning 1997 [Thinning investigation 1997]. Meddelanden 8. National Board of Forestry. Jönköping, Sweden.

Eliasson, L. 1998. Analysis of single-grip harvester productivity. Acta Universitatis Agriculturae Sueciae Silvestria 80. PhD thesis. Swedish University of Agricultural Sciences. Umeå, Sweden.

Eliasson, L. 1999. Simulation of thinning with a single-grip harvester. Forest Science 45(1), 26-34.

Fryk, J., Larsson, M., Myhrman, D. and Nordansjö, I. 1991. Forest Operations in Sweden. Forskningsstiftelsen Skogsarbeten. Kista, Sweden.

Gellerstedt, S. 1993. Thinning with a forestry machine - the mental and physical work. Research notes 244. Department of Operational Efficiency, Swedish University of Agricultural Sciences. Garpenberg, Umeå.

Gerasimov, Y. Y. and Siounev, V. S. 1997. Harvester crane key parameters: optimization in European Russian pines. International Journal of Forest Engineering 8(1), 63-74.

Gerasimov, Y. Y. and Siounev, V. S. 1998. Forest machinery crane compound scheme synthesis: "Skeleton" part. International Journal of Forest Engineering 9(1), 25-30.

Gerasimov, Y. Y. and Siounev, V. S. 2000. Forest machinery crane compound scheme synthesis: optimization of hydraulic cylinder operating mechanism. International Journal of Forest Engineering 11(1), 73-79.

Gustafsson, J. 1979. Forest drainage – methods, techniques and planning. Redogörelse No 1. Forskningsstiftelsen Skogsarbeten. Stockholm, Sweden.

IUFRO WP 3.04.02 1995. Forest work study nomenclature. Test edition valid 1995-2000. Department of Operational Effeciency, Swedish University of Agricultural Sciences. Garpenberg, Sweden.

Kofman, P. D. 1995. SIWORK 3, Ver. 1.1. Work study and field data collection system based on Husky Hunter handheld computer. Danish Forest and Landscape Research Institute. Vejle, Denmark.

Kärhä, K., Jouhiaho, A., Mutikainen, A. and Mattila, S. 2005. Mechanized energy wood harvesting from early thinnings. International Journal of Forest Engineering 16(1), pp. 15-26.

Lagesson, H. 1997. Effects of thinning type on the harvester productivity and on the residual stand. International Journal of Forest Engineering 8(2), 7-14.

Nakagawa, M., Hamatsu, J., Saitou, T. and Ishida, H. 2007. Effect of tree size on productivity and time required for work elements in selective thinning by a harvester. International Journal of Forest Engineering 18(2), 24-28.

Nurminen, T., Korpunen, H. and Uusitalo, J. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica 40(2), 335-363.

Nåbo, A. 1990. Operator workload in forest machines. Studies in precommercial thinning-, thinning and final felling operations. Report No. 185. Department of Operational Efficiency, Swedish University of Agricultural Sciences. Garpenberg, Umeå.

Ovaskainen, H., Uusitalo, J. and Väätäinen, K. 2004. Characteristics and significance of a harvester operators' working technique in thinning. International Journal of Forest Engineering 15(2), 67-78.

Sirén, M. and Aaltio, H. 2003. Productivity and cost of thinning harvesters and harvester-forwarders. International Journal of Forest Engineering 14(1), 39-48.

Talbot, B., Nordfjell, T. and Suadicani, K. 2003. Assessing the utility of two integrated harvester-forwarder machine concepts through stand-level simulation. International Journal of Forest Engineering 14(2), 31-43.

Vasiliauskas, R. 2001. Damage to trees due to forestry operations and its pathological significance in temperate forests: a literature review. Forestry 74(4), 319-336.

Tables and Figures

Table 1. Description of the simulation stands

Variable	Stand: Sparse (No. 203)	Stand: Dense (No. 602)
Standing volume *(m^3 u.b. ha^{-1})* [a]	104	198
Stand density *(trees ha^{-1})*	1760	2850
Mean diameter at breast height *(cm)*	11.3	11.7
Mean height *(m)*	10.1	11.3
Basal area at breast height *(m^2 ha^{-1})*	19.0	31.7

[a] m^3 solid stem wood under bark per hectare

Table 2. Description of the field study treatment units and their blocking

	Before thinning				Harvested trees'							
Block	Stand density *(trees ha^{-1})*		Volume *(m^3 u.b. ha^{-1})*		Number *(n ha^{-1})*		Volume *(m^3 u.b. ha^{-1})*		Mean diam. *(cm brh)*		Mean size *(m^3 u.b.)*	
	POB [a]	C [b]	POB	C	POB	C	POB	C	POB	C	POB	C
1	2190	2220	108.5	119.1	940	950	32.4	43.9	9.1	10.1	0.034	0.045
2	2360	2280	117.5	153.3	950	870	33.9	55.9	9.4	11.1	0.036	0.064
3	1230	1280	156.8	149.0	390	350	28.7	25.6	11.4	11.8	0.076	0.073
4	2600	2840	96.3	113.5	930	910	25.6	26.5	8.2	8.4	0.028	0.029
5	2930	3100	118.7	99.1	990	1000	33.9	24.6	9.0	8.0	0.034	0.025
6	2460	2130	116.6	115.1	800	750	33.1	41.5	9.5	12.0	0.041	0.056
Mean	2295	2308	119.1	124.9	833	805	31.3	36.3	9.4	10.3	0.041	0.049
SD [c]	578	634	20.3	21.5	227	238	3.4	12.8	1.1	1.8	0.017	0.019

[a] POB = Pivoting outer boom crane; [b] C= Conventional crane; [c] SD = standard deviation.

Table 3. Work elements used in the study

Work element	Definition	Priority
Felling and processing	Started when the harvesting head gripped the stem and stopped when the last log left the harvester head.	1
Machine movement forward	When the harvester's wheels were rolling forward.	2
Machine movement backward	When the harvester's wheels were rolling backward.	2
Crane out	Started when the crane was moved from the harvester towards a stem, ended when an element with a higher priority started or when the movement ended.	3
Crane in	Started when the harvester head was moved towards the machine without any merchantable log, ended when an element with a higher priority started or when the movement ended.	3
Waiting	No part of the machine was moving, but the operator was working with e.g. selecting what tree to cut.	3
Miscellaneous	Productive work that did not belong to any of the elements above, e.g. log and slash rearranging, brush cleaning and chain change.	3
Delay	Non-productive time due to operational, mechanical and personal reasons. Not included in the analyses.	3

Table 4. Simulated machine movement distance, trees thinned per position and the proportional time expenditure over crane types, stands and thinning intensity

Stand	Thinning intensity *(% of tree numbers)*	Machine movement distance *(m, mean and (SD))*		Thinned trees per position *(n, mean and (SD))*		POB crane's time saving *(% of time consumption for conventional crane)*	
		POB[a]	C[b]	POB	C	Machine movement time	Total time
Sparse	35	5.0 (0) [a]	3.7 (1.6) [b]	6.6 (2.8) [1]	4.9 (2.6) [1]	17.0	4.3
	50	5.0 (0) [a]	3.4 (0.9) [b]	8.0 (3.2) [1]	5.5 (2.3) [1]	21.0	5.3
Dense	35	4.7 (1.0) [a]	2.6 (1.2) [b]	10.0 (3.2) [1]	5.6 (2.7) [2]	32.0	8.0
	50	4.8 (0.5) [a]	2.9 (0.8) [b]	13.9 (3.6) [1]	9.4 (3.8) [2]	18.0	4.5

[a] POB = Pivoting outer boom crane; [b] C= Conventional crane. Within rows, superscript letters and numbers indicate significant ($p < 0.05$) differences for machine movement distances and thinned trees per position, respectively.

Table 5. Field study results: corrected mean times per crane type and work element (cmin per m^3 u.b.) at a common mean stem volume of 0.039 m^3 u.b., level of significance (*p*-values) and explained share of variance (adjusted R^2) from the analyses of variance of the elements' time consumption per harvested m^3 u.b. Error DF = 5 and 4 for models with 0 and 1 covariate, respectively

Work element	Crane		Treatment	Block	Covariate	Adj-$R^{2\,d}$
	POB[a]	C[b]	(*Crane*)		($1 / V_{tree}$)[c]	(%)
Felling and processing	445.5	475.9	0.066	0.042	0.002	97.6
Machine movement forward	79.0	90.4	0.204	0.231	0.028	61.9
Machine movement backward	3.9	16.5	0.003	0.087		80.0
Crane out	283.5	311.9	0.007	0.003	0.000	99.4
Crane in	60.1	71.5	0.353	0.041		67.6
Waiting	-	2.4	0.062	0.500		30.1
Miscellaneous	8.8	8.7	0.978	0.291		18.0
Total	879.2	978.9	0.002	0.001	0.000	99.4

[a] POB = Pivoting outer boom crane; [b] C= Conventional crane; [c] V_{tree}= harvested mean tree size in m^3 u.b;
[d] Adj-R^2= Adjusted R^2 value.

Table 6. Field study results: corrected mean values per crane type and variable, level of significance (*p*-values) and explained share of variance (adjusted R^2) from the analyses of variance. Error DF = 5 and 4 for models with 0 and 1 covariate, respectively

Variable	Crane		Treatment	Block	Covariate	Adj-R^2 [e]
	POB[a]	C[b]	(*Crane*)		TI_{vol}[d]	(%)
Machine movement forward (*n/ha*)	218	223	0.702	0.059		61.2
Machine movement backward (*n/ha*)	18	62	0.007	0.114		72.7
Trees per machine position	3.4	2.9	0.000	0.000	0.000	99.9
Log piles (*n/ha*)	287	300	0.286	0.169		41.9
Damaged trees (%)	6.8	7.9	0.392	0.417		8.1

[a] POB = Pivoting outer boom crane; [b] C= Conventional crane; [d] TI_{vol} = Thinning intensity (percentage of stand volume); [e] Adj-R^2= Adjusted R^2 value.

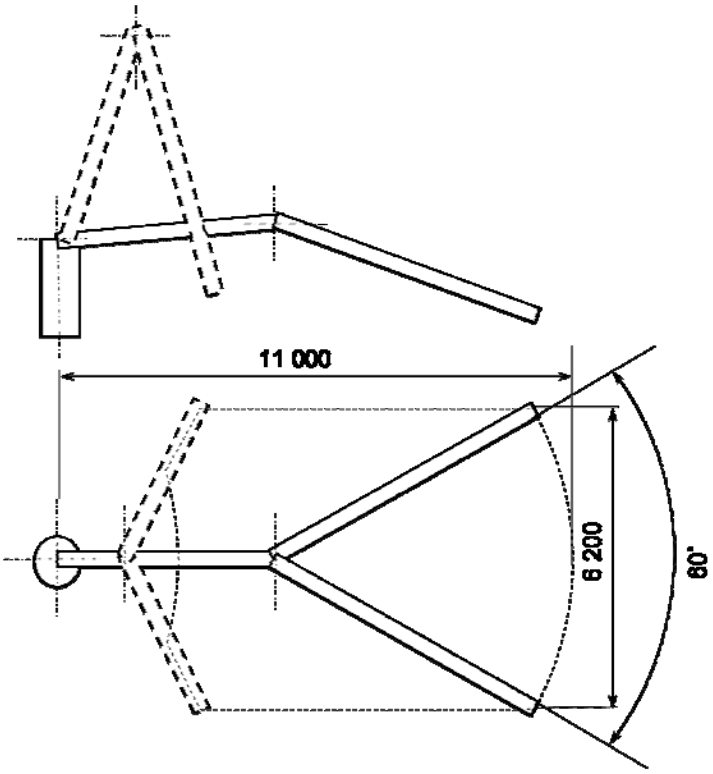

Figure 1. The pivoting outer boom crane and the crane pillar to the left (measures in mm). Thick full line is extended crane and thick dotted line is when the crane is drawn in. (Above) side view. (Below) top view, with fully right and left pivoting function indicated. The area with thin dotted lines indicates the area on ground that can be reached without turning the crane pillar.

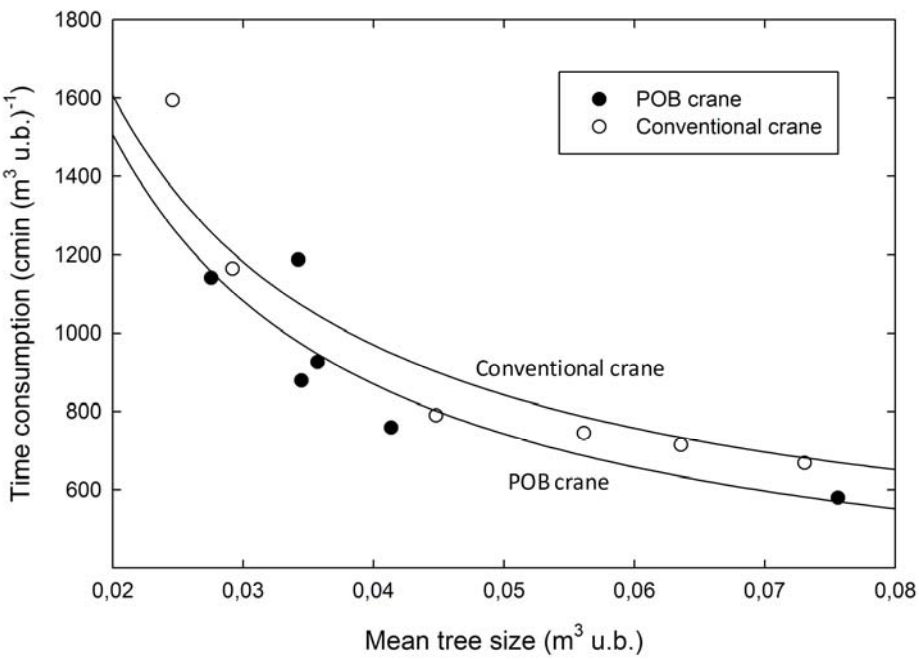

Figure 2. Predicting time consumption functions (Eq. [**5**]) and observed total time consumption in thinning for each treatment unit versus mean tree size.