

# Cutting Corners with a New Crane Concept

Ola Lindroos, Dan Bergström,  
Petter Johansson, and Tomas Nordfjell

## 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 in thinning between a conventional crane and a pivoting outer boom (POB) crane 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 1,230 to 3,100 trees per hectare and tree choice was restricted.

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

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

## Introduction

Conducting thinning operations with a harvester according to the cut-to-length (CTL) 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 1,000 to 1,500 trees per hectare are to be left undamaged (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 harvesting productivity

in this difficult operation (Fryk et al. 1991, Nurminen et al. 2006).

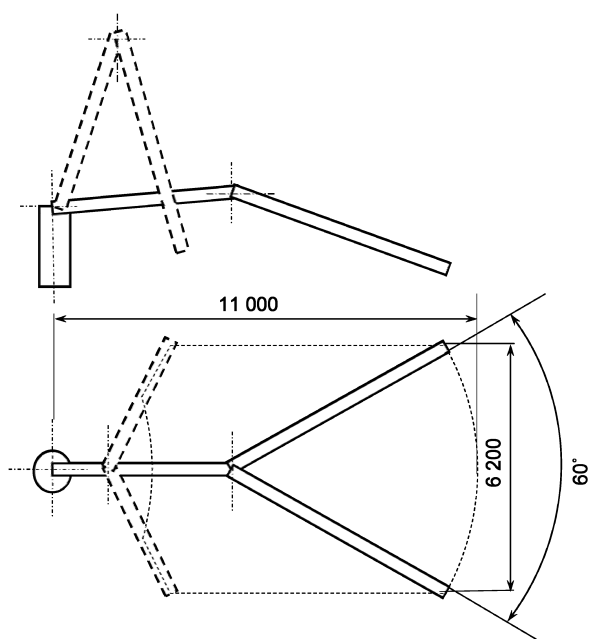
One important component of a harvester is the crane. In this paper, the term crane refers to the system of hydraulic cylinders and mechanical levers (Gerasimov and Siounev 2000) (i.e., crane pillar, mid boom, outer boom, and extending boom). While boom is often used as a synonym for crane, that usage is avoided in this paper so there is no confusion between the system and its components. One of the limiting factors of thinning productivity is the work required to reach trees selected for removal without damaging residual trees. Since most harvester cranes can only pivot (horizontally rotate) at the crane pillar, linear movements must be used to reach the tree. The distance from the crane pillar to the harvester head is no more than 11 m. To avoid damage to the residual trees, the movements of the crane generally have to be slow (Bergström et al. 2007). In addition, the machine often has to be repositioned short distances on the strip road. Depending on difficulties in reaching a specific tree, repositioning may also include short reversing movements (Eliasson 1999). Reversing is generally associated with decreased productivity (Ovaskainen et al. 2004). A crane that allows a nonlinear movement of the harvester head could reduce these problems. In theory, more trees selected for removal could be reached from a given machine position and crane speed could be higher since the distance to residual trees could be increased. A new harvester crane concept developed by 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 been used on backhoe loaders to enable ditches to be made parallel to the road on which the backhoe loader is driven (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 for determining 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; a simulation study conducted before the first POB crane was

---

The authors are, respectively, PhD (ola.lindroos@srh.slu.se), Dept. of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden; PhD Student (dan.bergstrom@srh.slu.se), Dept. of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden; MSc (petter.johansson@sveaskog.se), Sveaskog, Lycksele, Sweden; and Professor (tomas.nordfjell@srh.slu.se), Dept. of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden. This paper was received for publication in August 2008.  
© Forest Products Society 2008.

International Journal of Forest Engineering 19(2): 21-27.



**Figure 1.** ~ (Top) A side view of the POB crane with the crane pillar on the left (measurements in mm). The thick full line is the extended crane and the thick dotted line is when the crane is drawn in. (Bottom) A top view with the right and left pivoting function indicated. The area shown with the thin dotted lines indicates the area on the ground that can be reached without turning the crane pillar.

built is combined 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 (u.b.) through a 5 percent reduction of the total volumes. The two stands were chosen to represent the outer extremes in early thinnings of Swedish forests managed for roundwood production, in terms of stand density and standing volume. The position of the trees was identified using Cartesian coordinates. The stands were 40 by 25 m (0.1 ha), of which 40 by 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  $\pm 30^\circ$  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 predeter-

**Table 1.** ~ Description of the simulation stands.

Variable	Stand	
	Sparse (No. 203)	Dense (No. 602)
Standing volume ( $\text{m}^3$ u.b. $\text{ha}^{-1}$ ) <sup>a</sup>	104	198
Stand density (trees $\text{ha}^{-1}$ )	1,760	2,850
Mean diameter at breast height (cm)	11.3	11.7
Mean height (m)	10.1	11.3
Basal area at breast height ( $\text{m}^2$ $\text{ha}^{-1}$ )	19.0	31.7

<sup>a</sup>  $\text{m}^3$  solid stem wood under bark per hectare.

mined for selective thinning was chosen (i.e., the number of trees harvested in the strip road was not considered in the positioning decision). No backward machine movements 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 percent and 57.5 percent of the total number of removed trees in the sparse stand with a thinning intensity of 35 percent and 50 percent, respectively. In the dense stand, the equivalent shares of trees removed in the strip road were 76.1 percent and 58.4 percent.

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 ( $T_{\text{MOVE}}$ , s  $\text{ha}^{-1}$ ) was calculated according to Equation [1] (Eliasson 1999).

$$T_{\text{MOVE}} = (C \times N + \Sigma S / v) \quad [1]$$

where:

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

Based on values provided by Eliasson (1998),  $C$  was set to 5 s and  $v$  was set to  $1 \text{ m s}^{-1}$ . Machine repositioning time in a stand was set to 25 percent of the total time for the thinning operation, based on values supplied by Lagesson (1997). Consequently, machine repositioning time was multiplied by 4 in order to obtain total time for the thinning 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 by 20 m (0.1 ha) were created. All of the 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,

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

Block	Before thinning				Harvested trees							
	Stand density (trees ha <sup>-1</sup> )		Volume (m <sup>3</sup> u.b. ha <sup>-1</sup> )		Number (n ha <sup>-1</sup> )		Volume (m <sup>3</sup> u.b. ha <sup>-1</sup> )		Mean diameter (cm brh)		Mean size (m <sup>3</sup> u.b.)	
	POB <sup>a</sup>	C <sup>b</sup>	POB	C	POB	C	POB	C	POB	C	POB	C
1	2,190	2,220	108.5	119.1	940	950	32.4	43.9	9.1	10.1	0.034	0.045
2	2,360	2,280	117.5	153.3	950	870	33.9	55.9	9.4	11.1	0.036	0.064
3	1,230	1,280	156.8	149.0	390	350	28.7	25.6	11.4	11.8	0.076	0.073
4	2,600	2,840	96.3	113.5	930	910	25.6	26.5	8.2	8.4	0.028	0.029
5	2,930	3,100	118.7	99.1	990	1,000	33.9	24.6	9.0	8.0	0.034	0.025
6	2,460	2,130	116.6	115.1	800	750	33.1	41.5	9.5	12.0	0.041	0.056
Mean	2,295	2,308	119.1	124.9	833	805	31.3	36.3	9.4	10.3	0.041	0.049
SD <sup>c</sup>	578	634	20.3	21.5	227	238	3.4	12.8	1.1	1.8	0.017	0.019

<sup>a</sup> POB = pivoting outer boom crane.

<sup>b</sup> C = conventional crane.

<sup>c</sup> SD = standard deviation.

number, and mean diameter at breast height (DBH) (1.3 m) 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 the other blocks had not 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 percent uphill and was on even ground for the conventional crane and POB treatment units, respectively. In Block 6, the strip road used by the conventional crane sloped 31 percent uphill, while the strip road used by the POB crane sloped 30 percent downhill.

All of the trees were numbered and their DBH 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 approximately 10 randomly chosen and height-measured trees for each treatment unit. Based on Brandel's smaller volume function (1990), the height and diameters of all of the sampled trees, DBH based volume functions, were created for pine, spruce (*Picea abies*), and birch (*Betula* spp.) (Equations [2] through [4]). The functions were used to calculate tree volumes for the study. The volume unit used was m<sup>3</sup> solid stem wood u.b. with the stump excluded (m<sup>3</sup> u.b.).

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

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

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

where:

$V$  = stem volume under bark (m<sup>3</sup> u.b.); subscripts  $P$ ,  $S$ , and  $B$  are pine, spruce, and birch, respectively.

$D$  = stem DBH (1.3 m) on bark (cm).

The two treatments tested in the study were thinning by use of a POB crane and by a conventional crane. The single-grip harvester used in the study was a Valmet 911.3, which has a total mass of approximately 17 tonnes, and the crane and cabin are 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 the crane's POB function was not used. The operator was a 26-year-old man who had been operating harvesters for 4 years, of which 7 months were 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 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 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 work elements 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 percent 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 identity of the harvested tree 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

**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 toward 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 toward 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 (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 (mean with standard deviation in parentheses).*

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

Within rows, different superscript letters and numbers indicate significant ( $p < 0.05$ ) differences for machine movement distances and thinned trees per position, respectively.

damaged if the stem's bark was removed on a total area of 9 cm<sup>2</sup>, 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. The proportional difference in time consumption between crane types was also calculated, both for machine repositioning time and for 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 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<sup>3</sup> u.b. while number of machine movements and log piles were analyzed per hectare. The 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 percent.

## Results

### Simulation Study

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

### Field Study

The mean time consumption per thinned m<sup>3</sup> u.b. at a mean harvested stem volume of 0.039 m<sup>3</sup> u.b. was significantly lower when the POB crane was used compared to the conventional crane ( $p = 0.002$ ) (Table 5). Crane type significantly impacted the work elements machine movement backwards and crane out (Table 5). The time required for the work elements waiting

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

Work element	Crane		Treatment (crane)	Block	Covariate (1 / V <sub>tree</sub> ) <sup>c</sup>	Adjusted R <sup>2</sup> value (%)
	POB <sup>a</sup>	C <sup>b</sup>				
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

<sup>a</sup> POB = pivoting outer boom crane.

<sup>b</sup> C = conventional crane.

<sup>c</sup> V<sub>tree</sub> = harvested mean tree size in m<sup>3</sup> u.b.

and felling and processing was shorter with the POB crane than with the conventional crane, but the differences were just beyond the significance limit (*p* = 0.062 and 0.066, respectively). Time consumption was significantly influenced by mean tree size (Fig. 2), with a hyperbolic pattern. Consequently, the reciprocal of mean tree volume of harvested trees (V<sup>-1</sup>) 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<sup>-1</sup>, the plain mean tree volume and its square, alone or combined, did not improve the model additionally, except for the 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<sup>2</sup> 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* ≥ 0.075). 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 total time consumption per m<sup>3</sup> u.b.

$$T = 332.4 + 25.486 / V - 99.7 \times POB \quad [5]$$

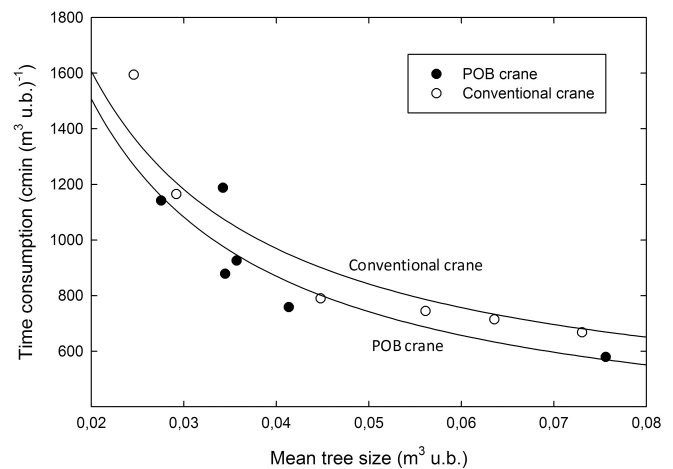
where:

*T* = total time consumption (cmin) per harvested m<sup>3</sup> u.b.

*V* = harvested mean tree size in m<sup>3</sup> u.b.

*POB* = dummy variable which assumes a value of 1 if a POB crane is used and 0 if a conventional crane is used.

Due to the dummy variable in the model (Eq. [5]), the POB crane is 99.7 cmin faster per m<sup>3</sup> 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<sup>3</sup> u.b., the POB crane is 7.2



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

percent and 14.8 percent faster, respectively, compared to the conventional crane.

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

When using the 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 covariates stand density, number of trees harvested, or thinning intensity (percent of trees) contributed significantly to the model (*p* ≥ 0.081).

The number of harvested trees per machine position was significantly higher when using the 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<sup>2</sup> value from 84.9 to 99.9 percent with all factors significant (*p* = 0.000). The adjusted

**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*<sup>2</sup>) from the ANOVA. Error DF = 5 and 4 for models with 0 and 1 covariate, respectively.

Work element	Crane		Treatment (crane)	Block	Covariate (TI <sub>vol</sub> ) <sup>c</sup>	Adjusted R <sup>2</sup> value (%)
	POB <sup>a</sup>	C <sup>b</sup>				
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
Harvested 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

<sup>a</sup> POB = pivoting outer boom crane.

<sup>b</sup> C = conventional crane.

<sup>c</sup> TI<sub>vol</sub> = thinning intensity (percentage of stand volume).

mean values were 3.4 trees per position for the POB crane and 2.9 for the 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 the POB crane and the conventional crane (Table 6). The mean number of piles for the six replicates was 286.7 per hectare for the POB crane and 300.0 for the 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 the POB crane and the conventional crane (Table 6). Their mean ratios for the six replicates was 6.8 percent for the POB crane and 7.9 percent for the conventional crane, with a mean difference within blocks of 1.1 percent (SD 2.8).

## Discussion

In the comparative field study, as many of the influencing factors as possible were kept constant. 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. In addition to machine and stand effects, the influence of machine operator is always crucial in comparative time studies, especially when using few operators. In this case, the 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 to 0.079 m<sup>3</sup> u.b.) harvested in the field study, the observed productivity tallied reasonably with other contemporary CTL 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<sup>3</sup> u.b. implies a productivity of 6.8 and 6.1 m<sup>3</sup> u.b. per effective hour (i.e., 175 and 157 trees per effective hr) for the 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 influ-

enced work with a conventional crane in a negative way. Moreover, even though the experimental design attempted to compare 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. But 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 also indicated, however, that other work elements might be positively influenced in the use of the POB crane. Despite these 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 the number 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 the POB and conventional thinning were higher than the Swedish recommendations (< 5% residual trees with damages ≥ 15 cm<sup>2</sup> (Bräcke 1998)). The found damages, however, were modest compared to many other studies (Vasiliaskas 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 reach of the POB crane 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. This supposition needs to be proven empirically.

In the CTL 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.

Theoretically the extra 175 kg mass of the POB crane decreased the lifting capacity at full reach by 85 kg. 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. Because the same crane was used for both crane types, however, 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. This study supports that statement and indicates that it is also 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 (3,000 to 5,000 trees per ha), young stands (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 efficiency of the POB crane is recommended, mainly on the effect of free tree choice, thinning of larger trees, and stands with limited visibility. The effect of different pivoting angles and the placement of the crane in relation to the cabin is also of interest for further investigations.

### Literature Cited

Bergström, D., U. Bergsten, T. Nordfjell, and T. Lundmark. 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. Dept. of Forest Yield, Swedish Univ. of Agricultural Sciences, Garpenberg.  
 Bredberg, C.-J. 1972. Type stands for the first thinning. Research Notes 55. Dept. 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 Univ. of Agricultural Sciences, Umeå, Sweden.  
 Eliasson, L. 1999. Simulation of thinning with a single-grip harvester. *Forest Sci.* 45(1): 26-34.  
 Fryk, J., M. Larsson, D. Myhrman, and I. Nordansjö. 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. Dept. of Operational Efficiency, Swedish Univ. of Agricultural Sciences, Garpenberg, Umeå.  
 Gerasimov, Y.Y. and V.S. Siounev. 1997. Harvester crane key parameters: Optimization in European Russian pines. *International J. of Forest Engineering*. 8(1): 63-74.  
 Gerasimov, Y.Y. and V.S. Siounev. 1998. Forest machinery crane compound scheme synthesis: "Skeleton" part. *International J. of Forest Engineering*. 9(1): 25-30.  
 Gerasimov, Y.Y. and V.S. Siounev. 2000. Forest machinery crane compound scheme synthesis: Optimization of hydraulic cylinder operating mechanism. *International J. 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. Dept. of Operational Efficiency, Swedish Univ. 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., A. Jouhiahio, A. Mutikainen, and S. Mattila. 2005. Mechanized energy wood harvesting from early thinnings. *International J. of Forest Engineering*. 16(1): 15-26.  
 Lagesson, H. 1997. Effects of thinning type on the harvester productivity and on the residual stand. *International J. of Forest Engineering*. 8(2): 7-14.  
 Nakagawa, M., J. Hamatsu, T. Saitou, and H. Ishida. 2007. Effect of tree size on productivity and time required for work elements in selective thinning by a harvester. *International J. of Forest Engineering*. 18(2): 24-28.  
 Nurminen, T., H. Korpunen, and J. Uusitalo. 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. Dept. of Operational Efficiency, Swedish Univ. of Agricultural Sciences, Garpenberg, Umeå.  
 Ovaskainen, H., J. Uusitalo, and K. Väätäinen. 2004. Characteristics and significance of a harvester operator' working technique in thinning. *International J. of Forest Engineering*. 15(2): 67-78.  
 Sirén, M. and H. Aaltio. 2003. Productivity and cost of thinning harvesters and harvester-forwarders. *International J. of Forest Engineering*. 14(1): 39-48.  
 Talbot, B., T. Nordfjell, and K. Suadicani. 2003. Assessing the utility of two integrated harvester-forwarder machine concepts through stand-level simulation. *International J. 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.