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Boom-tip control reduces novice operators' time consumption for crane work with harvesters - a standardised field experiment

Kranspitzensteuerung reduziert den Zeitaufwand von Anfängern bei Kranarbeiten mit Harvestern – ein standardisiertes Feldexperiment

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Keywords: automation, cut-to-length logging, operator assistance system, productivity, Smart Crane, thinning

Schlüsselbegriffe: Automatisierung, Durchforstung, Fahrerassistenzsystem, Produktivität, Smart Crane, Sortimentsverfahren

Abstract

In forestry, thinning operations place considerable cognitive demands on harvester operators. The operators are responsible not only for tree selection but also for manoeuvring the harvester head between the remaining trees without causing damage on them. Consequently, crane work accounts for approximately 90% of total time consumption during thinnings. Assistance systems facilitating crane work, such as boom-tip control (BTC), allow for improved productivity during thinning. With BTC, the operator controls the movement of the boom tip directly, rather than manipulating individual crane joints. We conducted a standardised field experiment simulating crane movement between remaining trees, as in thinning operations. The harvester used was a midsized (18-tonne) Komatsu 911, equipped with Smart Crane, *i.e.* Komatsu's version of BTC. The operators (n = 18) were students enrolled in a three-year forest machine operator education programme. Each experimental run involved visiting and gripping 13 standing stems with the harvester head. None of the stems

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were felled, allowing them to be reused throughout the experiment. We applied repeated-measures analysis of covariance to compare conventional boom control with Smart Crane. On average, operators completed the task 9.5% faster when they used Smart Crane. Based on our findings and current literature, BTC appears to offer greater time-saving potential in thinnings than during clearcutting. Furthermore, as most operators benefitted from BTC, we recommend full implementation of BTC on all new forest machines.

Zusammenfassung

In der Forstwirtschaft stellen Durchforstungen erhebliche kognitive Anforderungen an Harvesterfahrer. Diese sind nicht nur für die Baumwahl verantwortlich, sondern müssen den Harvesterkopf auch zwischen den verbleibenden Bäumen manövrieren, ohne diese zu beschädigen. So entfallen etwa 90 % der gesamten Arbeitszeit bei Durchforstungen auf die Kranarbeit. Assistenzsysteme, die die Kranarbeit erleichtern, wie zum Beispiel Kranspitzensteuerung (Boom-tip control, BTC) ermöglichen eine höhere Produktivität bei Durchforstungen. Mit BTC steuert der Fahrer die Bewegung der Kranspitze direkt, anstatt einzelne Krangelenke zu bedienen. Wir führten ein standardisiertes Feldexperiment durch, das die Kranbewegung zwischen den verbleibenden Bäumen – typisch für Durchforstungen – simulierte. Der eingesetzte Harvester war ein mittelgroßer (18 t) Komatsu 911, ausgestattet mit Smart Crane, d. h. der BTC-Version von Komatsu. Die Fahrer (n = 18) waren Schüler eines dreijährigen Ausbildungsprogramms für Forstmaschinenführer. Jeder Versuchsdurchlauf bestand darin, mit dem Harvesterkopf 13 stehende Stämme anzufahren und zu greifen. Keiner der Stämme wurde gefällt, sodass sie während des gesamten Experiments wiederverwendet werden konnten. Zur Auswertung wendeten wir eine Varianzanalyse mit Messwiederholung und Kovariatenkontrolle an, um die konventionelle Kransteuerung mit Smart Crane zu vergleichen. Im Durchschnitt erledigten die Fahrer die Aufgabe 9,5 % schneller, wenn sie Smart Crane verwendeten. Nach unseren Ergebnissen und der aktuellen Literatur bietet BTC bei Durchforstungen ein größeres Zeiteinsparungspotenzial als bei Kahlschlägen. Weil viele Fahrer von BTC profitierten, empfehlen wir die vollständige Ausstattung aller neuen Forstmaschinen mit diesem System.

1 Introduction

Crane work constitutes approximately 90% of harvester time consumption during thinnings (Pohjala *et al.* 2024, 2025). Therefore, assistance systems that facilitate harvester-crane work are of interest to improve harvester productivity during thinnings. Boom-tip control (BTC) is an example of this type of assistance systems. The development of BTC for forest machines began in 1980s (Löfgren 1989; Löfgren *et al.* 1994;

Löfgren & Wikander 2009), but it took three decades to finally launch a commercial BTC for forest machines in 2013 (Parker *et al.* 2016; Lindroos *et al.* 2017). When using conventional boom control, the operator must control each crane joint independently, coordinating the movements of individual crane parts to steer the boom-tip in the desired direction. Contrariwise, with BTC, the operator directly controls the boom-tip movement without needing to control the crane joints separately (Löfgren & Wikander 2009; Lindroos *et al.* 2017). BTC is a perceptive system that requires appropriate software and hydraulic cylinders with built-in sensors to monitor the movements of each crane joint (Figure 1). The software calculates how to adjust the length of each hydraulic cylinder on the crane to reach the desired boom-tip path. The technical principles of BTC are described *e.g.* in Löfgren and Wikander (2009).

During the standardised field experiment of Hartsch *et al.* (2024), BTC helped a professional operator reduce a forwarder's loading-crane cycle time by nearly 10%. According to the standardised field experiment of Manner *et al.* (2017), BTC can help beginners reduce the time consumption for forwarder-crane work by 25–30%. During the follow-up study of Manner *et al.* (2019), BTC facilitated seven professional forwarder operators to reduce total time consumption by on average 4%.

In the only scientifically published study on harvester-BTC, one of two participating operators saved 10% time with BTC, while the other operator neither saved nor lost time with BTC (Manner & Lundström 2025). That time study was conducted during routine clear-cutting operations. Although all time savings occurred exclusively when the harvester head was holding a stem/log, further analyses on BTC with an „empty" harvester head are of interest given that remaining trees are present (Manner & Lundström 2025). In Nordic forestry, harvester operators are responsible for tree selection during thinnings (Pohjala *et al.* 2024, 2025). BTC may facilitate the steering of the harvester head between the remaining trees; thereby easing the operators' mental load and improving productivity.

The objective of our study was to examine whether BTC reduces novice operators' time consumption during harvester-crane work when remaining trees are present. Until now, all scientific studies on BTC have focused solely on John Deere's system, Intelligent Boom Control. Although the general steering principles of boom-control systems (including BTC) are standardised across manufacturers (Figure 1), machine construction and ergonomics differ markedly between brands. Therefore, in our study, we selected a manufacturer other than John Deere.

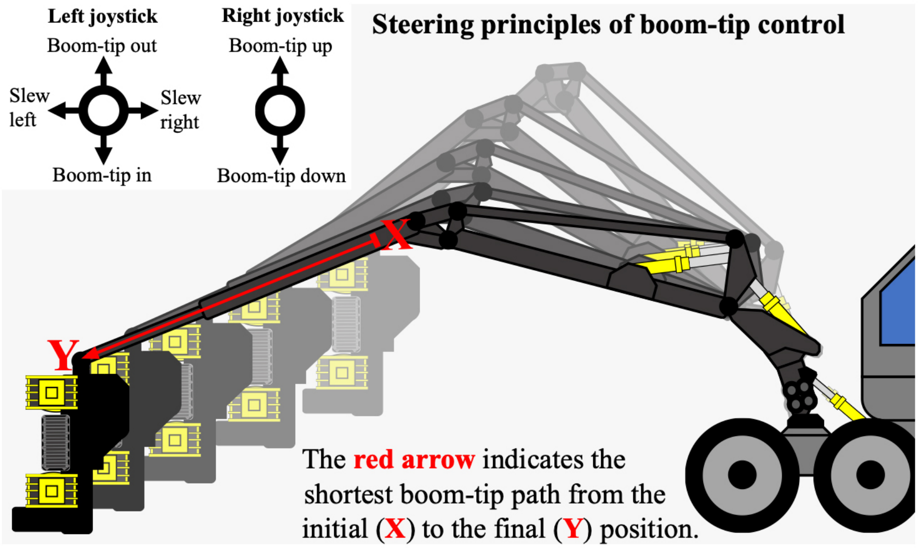

Figure 1: When using boom-tip control, pushing or pulling the left joystick moves the boom tip forward or backward; while moving the joystick sideways shifts the boom tip left or right. The right joystick controls vertical movement of the boom tip. Although the movement from point X to point Y may appear simple, it involves coordinated control of multiple crane joints. In contrast, using conventional boom control requires the operator to manage each crane joint independently to achieve the same movement. Such crane manoeuvring requires precisely controlling different crane parts to combine them into the desired boom-tip path.

Abbildung 1: Bei Verwendung von Kranspitzensteuerung bewegt das Drücken oder Ziehen des linken Joysticks die Kranspitze vorwärts oder rückwärts; seitliche Bewegungen des Joysticks verschieben die Kranspitze nach links oder rechts. Der rechte Joystick steuert die vertikale Bewegung der Kranspitze. Obwohl die Bewegung von Punkt X nach Punkt Y einfach wirkt, erfordert sie eine koordinierte Steuerung mehrerer Krangelenke. Im Gegensatz dazu muss der Fahrer bei konventioneller Kransteuerung jedes Krangelenk einzeln bedienen, um dieselbe Bewegung zu erreichen. Ein solches Kranmanövrieren erfordert eine präzise Steuerung der verschiedenen Kranteile, um sie zu einer gewünschten Bahn der Kranspitze zu kombinieren.

2 Material and Methods

2.1 Standardised field experiment setup

To address the objectives, we conducted a field study using a standardised experiment setup which mimicked one machine position in an imaginary thinning stand (Figure 2). The working sector was approximately 200 degrees with radius of ca 11 m and an area of approximately 210 m². On the ground, in front of the harvester, we used spray-painted sticks to clearly mark a point where the operator would assumingly have bucked the felled stems during real-life harvester work.

Thirteen stems (11 *Picea abies*, one *Betula* spp., one *Populus tremula*) were selected to be included in the study (Table 1), while the rest of the trees were harvested and removed from the experimental plot (Figure 2). Consequently, the final stem density within the experimental plot was 13 stems per 210 m² (approximately 620 stems/ha). The average diameter at breast height (DBH), measured over bark, was on average 24.0 cm, varying from 15.5 to 31.5 cm. The basal area of the plot was 0.61 m², corresponding to 28.9 m²/ha. The distance between the imaginary bucking point and the stems was on average 6.7 m, varying from 3.9 to 11.3 m.

The experimental plot was placed on a logging site where the surface structure was rated as 2 and the slope as 1 according to Swedish Terrain Classification System (Berg 1992). To maintain good visibility for the operators, we aligned the experimental plot to minimize work against the sun. The field experiment took place in March 2025, in central Sweden, 70 km north of Stockholm. The weather at the site during the four experiment days was above freezing, partly cloudy to sunny. Working conditions were good through the study.

2.2 Machine and operators

In our study, we used a six-wheeled midsized (18-tonne) Komatsu 911 harvester (model year 2024). The machine was equipped with a C6 crane (reach 11 m), a S92 harvester head, and with a rotating and levelling cabin. Most essentially, the machine was equipped with a Smart Crane which is Komatsu's product name for BTC. When Smart Crane is deactivated, the boom-control system functions as a conventional boom control.

Operators (one female and 17 males) were students at the Jälla vocational upper secondary school in central Sweden who were conducting their three-year education to become forest-machine operators. Before the experiment, their experience of operating harvesters varied from null to four weeks. The operators' average age was 18 years varying from 17 to 22 years.

2.3 Experimental run

During an experimental run (*i.e.* a complete observation), each of the 13 selected stems were visited and gripped with the harvester head (Figure 2). We numbered the stems with paint to indicate the order they were to be visited and gripped. None of the stems were felled during the experiment, allowing us to use the same 13 stems throughout the experiment.

Each experimental run started with the harvester head at the starting point (Figure 2). Timing began when the harvester head left the starting point as the operator steered the harvester head to the first stem. Then the operator opened the harvester head and set it against the stem number 1 and closed the harvester head around the stem (gripping it). After that, the operator adjusted the harvester head for felling position, i.e. the harvester head was lowered to approximately the ground level. At this stage, a real-life operator would have conducted a felling cut. But in our experiment, the operator instead opened the harvester head (releasing the stem) and steered the harvester head back to the starting position. After that, the operator steered the harvester head to the second stem (Figure 2), and the same steps were repeated for the stem number 2. This exact same procedure continued until all 13 stems were visited and gripped with the harvester head. Timing ended when the operator had steered the harvester head back to the starting/finishing point from the stem number 13.

To mimic real-life thinning operations where damaging the remaining trees must be avoided, harvester head (or crane) was allowed only touch the specific stem that was to be visited and gripped with the harvester head during the crane cycle. Operators were not informed of their times to minimise the risk of the study becoming a competition between operators. If an operator was disturbed and/or did a mistake, the experimental run was redone.

Table 1: Descriptive statistics of the stems used during the field experiment. Stems were visited and gripped with the harvester head in the same order throughout the experiment according to stem numbers. The stem numbers are followed by the distance between the starting/finishing point and the specific stem, tree species, and diameter at breast height (DBH). The positions of the stems in relation to the harvester are shown in Figure 2.

Tabelle 1: Deskriptive Statistiken der im Feldexperiment verwendeten Stämme. Die Stämme wurden während des gesamten Experiments in derselben Reihenfolge entsprechend der Stammnummern mit dem Harvesterkopf angefahren und gegriffen. Auf die Stammnummern folgen der Abstand zwischen Start-/Endpunkt und dem jeweiligen Stamm, die Baumart sowie der Durchmesser in Brusthöhe (DBH). Die Positionen der Stämme in Relation zum Harvester sind in Abbildung 2 dargestellt.

Stem number	Distance (m)	Tree species	DBH (cm)
1	4.4	*Picea abies*	21.0
2	11.3	*Picea abies*	29.0
3	9.1	*Picea abies*	23.0
4	7.7	*Picea abies*	27.0
5	6.2	*Betula* spp.	15.5
6	6.0	*Picea abies*	25.5
7	4.4	*Populus tremula*	31.5
8	5.7	*Picea abies*	19.8
9	3.9	*Picea abies*	25.5
10	6.5	*Picea abies*	24.0
11	4.9	*Picea abies*	23.5
12	6.7	*Picea abies*	19.7
13	10.5	*Picea abies*	27.1

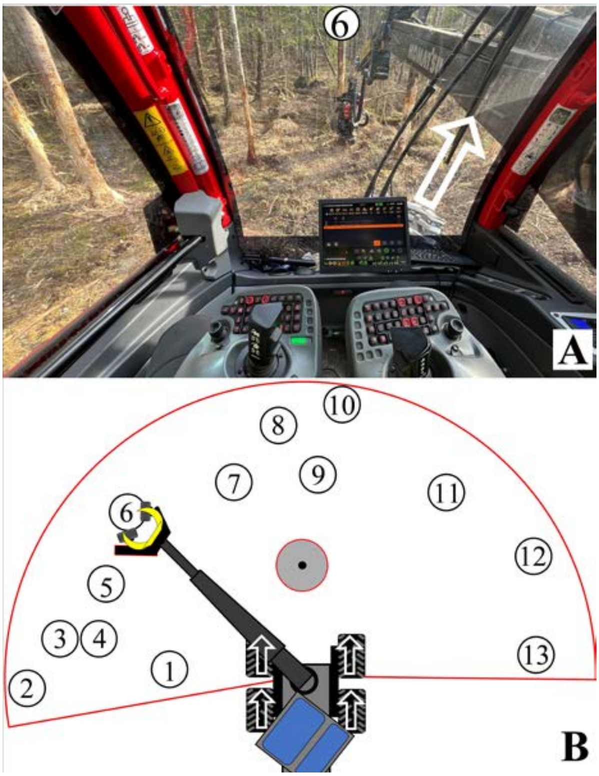

Figure 2: The illustration (B) visualizes the standardised field-experiment setup. The grey circle in front of the machine marks the starting/finishing position of an experimental run. Black circles represent the positions of the stems, and the numbers in black boxes indicate the order in which the stems were visited and gripped with the harvester head. The experimental plot roughly formed a semicircle, corresponding to the crane's maximum reach (i.e. 11 m). The operator's view during the experiment is shown in the photo (A). The photo and illustration capture the same moment (though aligned differently): the operator is gripping stem number 6 on the left-hand side, and the cabin and crane are aligned accordingly. White arrows indicate the front bogies' alignment (i.e. driving direction). The machine remained stationary throughout the experiment. The stems' diameter at breast height, tree species, and their distance from the starting/finishing position are provided in Table 1.

Abbildung 2: Die Abbildung (B) veranschaulicht den standardisierten Versuchsaufbau im Feld. Der graue Kreis vor der Maschine markiert die Start-/Endposition eines Versuchsdurchlaufs. Schwarze Kreise zeigen die Positionen der Stämme, und die Zahlen in schwarzen Kästchen geben die Reihenfolge an, in der die Stämme mit dem Harvesterkopf angefahren und gegriffen wurden. Die Versuchsfläche bildete ungefähr einen Halbkreis, entsprechend der maximalen Kranreichweite (d. h. 11 m). Die Sicht des Fahrers während des Experiments ist im Foto (B) dargestellt. Foto und Abbildung erfassen denselben Moment (wenn auch unterschiedlich ausgerichtet): Der Fahrer greift Stamm Nummer 6 auf der linken Seite und Kabine sowie Kran sind entsprechend ausgerichtet. Weiße Pfeile zeigen die Ausrichtung der vorderen Bogie-Achse. Die Maschine blieb während des gesamten Experiments stationär. Die Brusthöhendurchmesser (DBH), Baumarten und Abstände der Stämme zur Start-/Endposition sind in Tabelle 1 angegeben.

To avoid systematically benefiting either system (regarding learning curve etc.), every other operator conducted their first experimental run with Smart Crane activated and every other with Smart Crane deactivated. Thus, 9 operators started the experiment with Smart Crane, and 9 operators started with conventional boom control. Prior to the experiment, the crane speed was set to 40% of its maximum and the same crane settings were used throughout the experiment.

The unit of observation was a complete experimental run, which each operator repeated three times using Smart Crane and three times having it deactivated. Thus, the dataset contains six time observations per operator in total. Time consumption was recorded manually, and it includes only effective work; all delays were excluded.

2.4 Statistical analysis

We fitted a Repeated-Measures Analysis of Covariance (RM ANCOVA), implemented as a linear mixed model, to analyse the effect of experimental factors on time consumption (seconds per experimental run). Operator (n = 18) was treated as a random effect, and boom-control system (two levels: Smart Crane deactivated or activated) was included as a within-subject factor. Harvester operating experience (weeks) was included as a covariate to test whether experience had a systematic effect on productivity and to reduce residual variance. Post-hoc pairwise comparisons were conducted using the Tukey–Kramer method to adjust for multiple comparisons. Assumptions for RM ANCOVA – such as sphericity, normality of residuals, and homogeneity of regression slopes – were verified following the recommendations of Underwood (1997), Barrett (2011), and Tabachnick *et al.* (2019). All analyses were performed in SAS 9.4, with statistical significance set at 5%. Prior to statistical analyses, we visualized the raw data with boxplots to assess the distribution and variability of time consumption under each boom-control system (Figure 3A).

3 Results

With Smart Crane activated, time consumption decreased by 21.9 seconds per experimental run (Table 2). At the operators' average work experience level of 1.14 weeks, this decrease corresponded to 9.5%-time savings from 231.6 to 209.7 seconds per experimental run. Moreover, each week of harvester operating experience deceased time consumption by 22.0 seconds per experimental run (Table 2).

Table 2: Fixed effect estimates (seconds per experimental run) from the Repeated-Measures Analysis of Covariance. The estimates, when appropriate, are followed by the lower and the upper confidence limits of the 95% confidence intervals in brackets. Harvester operating experience (in weeks) is the covariate and the boom-control system (i.e. Smart Crane either deactivated or activated) is the categorical factor.

Tabelle 2: Schätzwerte der festen Effekte (Sekunden pro Versuchsdurchlauf) aus der Varianzanalyse mit Messwiederholung und Kovariatenkontrolle. Die Schätzwerte werden – sofern zutreffend – von den unteren und oberen Grenzen der 95%-Konfidenzintervalle in Klammern gefolgt. Die Berufserfahrung im Harvesterbetrieb (in Wochen) ist die Kovariate, und das Kransteuersystem (d. h. Smart Crane deaktiviert oder aktiviert) ist der kategoriale Faktor.

		Estimate	Standard Error	T-value	P-value	Degrees of Freedom
Intercept		256.67	13.50	19.01	-	0
Experience		-22.02 [-34.99; -9.05]	6.53	-3.37	0.0011	89
Smart Crane:	Activated	-21.89 [-32.58; -11.20]	5.38	-4.07	0.0001	89
	Deactivated	0	-	-	-	-

Residual diagnostics of the time-consumption model showed approximately symmetric distributions for both boom-control systems (Figure 3B). In the conventional boom-control condition (*i.e.* Smart Crane deactivated), residuals had a slightly lower median, reflecting a minor skew caused by a few operators who appeared to have notable difficulties with this control mode. The model accounted for operator-level variance through the random effect, and mean residuals across conditions were zero, with only minor heterogeneity in residual variances.

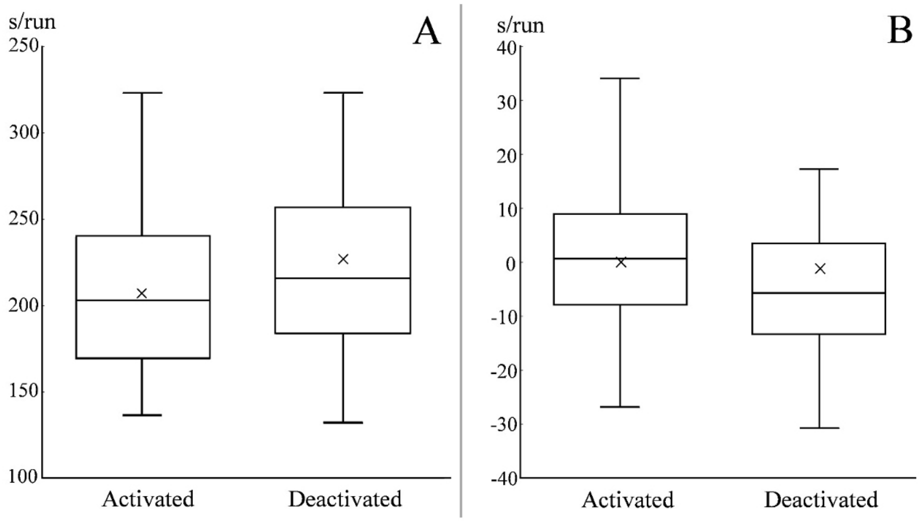

Figure 3: Time-consumption distributions (seconds per experimental run) by boom-control system (Smart Crane activated or deactivated) prior to statistical tests (A). Residual distributions from the time-consumption model by boom-control system (B). Interquartile ranges (IQRs) are shown with whiskers defined by Tukey's 1.5·IQR rule.

Abbildung 3: Verteilungen des Zeitaufwands (Sekunden pro Versuchsdurchlauf) nach Kransteuersystem (Smart Crane aktiviert oder deaktiviert) vor den statistischen Tests (A). Residuenverteilungen des Zeitaufwandsmodells nach Kransteuersystem (B). Die Interquartilsabstände (IQR) sind dargestellt, wobei die „Whisker" gemäß Tukeys 1,5·IQR-Regel definiert sind.

4 Discussion

4.1 Strengths and weaknesses of the study

Standardised experimental designs are common in forest work science (Häggström *et al.* 2016; Manner *et al.* 2017; Hartsch *et al.* 2024; Rossander *et al.* 2025). In standardised experiments, the factors influencing the results are easily controlled, but the absence of real harvesting limits the generalizability of the results to practical forestry. This was also the case in our study. Standardization allowed us to repeat each experimental run multiple times per operator, but we could not calculate actual harvester productivity because no trees were harvested.

Having professional operators participate in time studies is generally preferable. However, including novice operators enabled a much larger sample without making the experiments unrealistically costly. A large sample is crucial because productivity – and, most importantly, the effect of crane automation (*e.g.* BTC) – varies notably among forest-machine operators (Kärhä *et al.* 2004; Ovaskainen *et al.* 2004; Malinen *et al.* 2018; Englund *et al.* 2017; Manner *et al.* 2019; Manner & Lundström 2025).

The stems gripped during the experiment were thicker than those typically harvested during Nordic thinning operations. That said, thinner stems would have worn out during the experiment. Moreover, DBH does not affect time consumption of harvester work when the harvester head is not holding a stem/log (Manner & Lundström 2024).

In general, stand densities vary notably depending on stands' age and other silvicultural parameters. Within Swedish forestry, the stand density prior to latter thinning is typically 800–1100 stems/ha and post thinning 500–700 stems/ha, respectively (Skogskunskap 2024). Thus, the stand density during the experiment (620 stems/ha) mimics sufficiently the average density experienced by harvester operators during latter thinnings. Moreover, unlike in real-life thinning operations in Nordic forestry, the operators did not need to make any silvicultural decisions regarding tree selection, nor manoeuvre felled stems between remaining trees, during the experiment.

Thus, the experimental setup might have favoured conventional boom control. The stand density during the experiment could preferably have been somewhat higher to mimic denser stands and to make the experiment more demanding. That said, steering the crane between the trees is for novice operators a mentally demanding task *per se.*

4.2 Productivity improvement potential of crane automation (e.g. BTC)

The most productive forest-machine operators are 40–100% more productive than their less productive counterparts (Sirèn 1998; Kärhä *et al.* 2004). Variations in productivity do not solely depend on differences in operators' motorial ability to operate a crane, but a large part of productivity can be explained by differences in working methods (Ovaskainen 2009; Schmiedel *et al.* 2022). Because crane automation primarily only aids operators' ability to steer a crane, crane automation *per se* can only to some extent shrink productivity differences between operators. Thus, in that context, the time saving of 9.5% with activated Smart Crane is indeed notable.

Nevertheless, crane automation might provide even greater time savings if it enables more efficient working methods or is combined with artificial intelligence. Also, automation might have important role in the future, *e.g.* remote-controlled forest machines might notably benefit from crane automation (Lundbäck *et al.* 2022, 2023).

5 Conclusions

BTC reduces novice operators' time consumption during harvester-crane work even when the harvester head is not holding a stem, provided that remaining trees are present. This finding supports the notion that BTC (and crane automation in general) has greater time-saving potential in thinnings than in clearcuttings. According to our study and current literature, most operators benefit from using BTC. Therefore, we recommend full BTC-implementation on all new forest machines sold. Still, despite numerous research projects on crane automation, its impact on practical forest-machine work is not well documented. We therefore propose examining the effects of crane automation during real-life logging operations.

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