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Innovative productivity improvements in forest operations: a comparative study of the Assortment Grapple using a machine simulator

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Abstract: Because of generally small log piles, loading forwarders during thinning is time consuming. The Assortment Grapple, an innovative grapple with an extra pair of claws which facilitates the handling of two assortments during one loading crane cycle, has been designed to decrease forwarders' loading time consumption. A standardized experiment was performed in a virtual thinning stand using a machine simulator with the objectives to form guidelines for working with the Assortment Grapple and to analyse its development potential. Four experienced operators participated in the study. According to the results, the Assortment Grapple's accumulating function is beneficial only when there are no remaining trees between piles loaded during the same crane cycle. In such cases, none of participating operators lost time, and 3 of 4 operators saved time notably. The problem with the remaining trees is the extra time required to steer the crane tip around them. Therefore, a harvester should place those log piles that are later to be forwarded together in the same space with no remaining trees between the piles. Furthermore, we recommend that the Assortment Grapple's usability will be improved by adding an own rocker switch on the forwarder's controls to command the extra claws.

Keywords: crane; cut-to-length method; forwarder; loader; operator; thinning

A fully mechanised Nordic cut-to-length logging system consists of harvesters and forwarders. A harvester fells, delimbs, and crosscuts the stems into logs of different assortments. A forwarder picks up the logs and delivers them to a roadside landing.

To avoiding overly long driving distances, and hence to sustain high productivities, operators often decide to forward several assortments in a load (Kellogg, Bettinger 1994; Sirén, Aaltio 2003; Nurminen et al. 2006; Manner et al. 2013; Strandgard et. al 2017). Moreover, especially in thinnings, due to the small average pile-size, only a minor fraction of the grapple area is used (Gullberg 1997; Väätäinen et al. 2006). Consequently, many crane cycles are required to fill a forwarder's load, thereby increasing time consumption during loading.

Helsinge Skog Innovation AB introduced in spring 2014 a technical innovation called the Assortment Grapple (originally "Sortimentsgripen" in Swedish). In addition to the conventional claws, the Assort-

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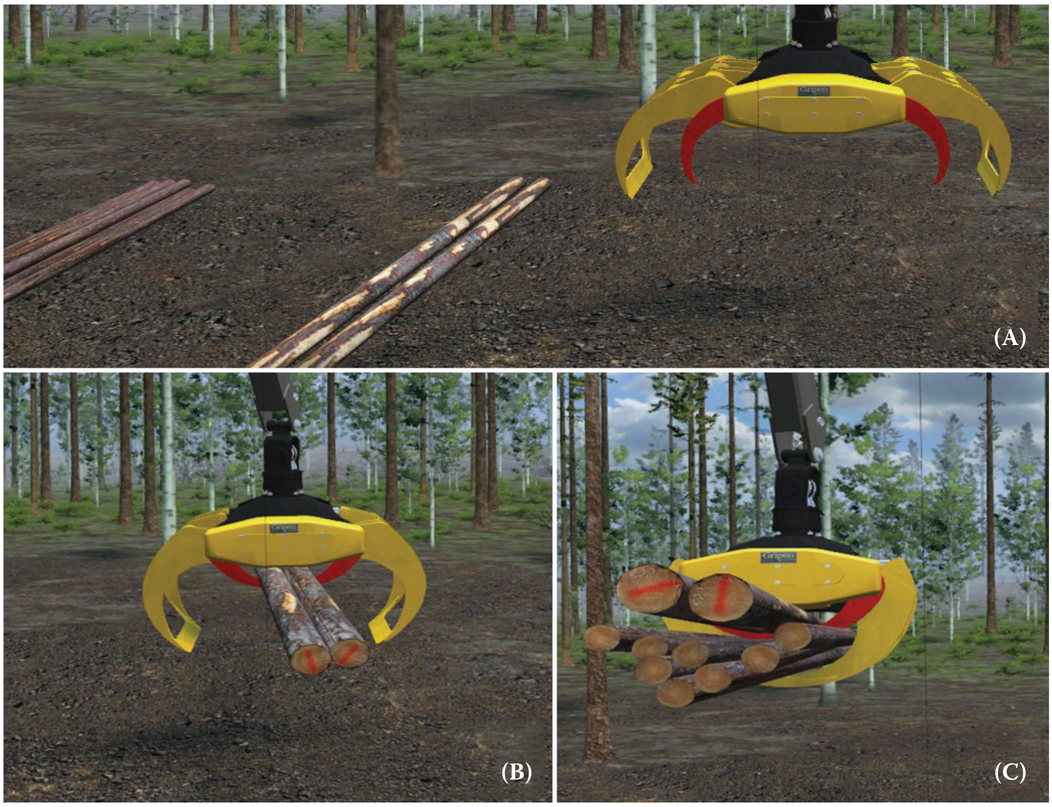

Figure 1. The Assortment Grapple comprises a standard grapple (here in yellow) fitted with an extra pair of claws (here in red) in addition to the conventional claws (A). The extra claws facilitate the handling of two assortments during one crane cycle (B, C)

ment Grapple has an extra pair of claws fitted on a standard grapple forming an assortment-handling (accumulating) function (Figure 1). The Assortment Grapple facilitates the handling of two assortments during one crane cycle, thereby intensifying the use of the grapple's capacity. More efficient use of the grapple's capacity should decrease the loading time consumption. The Assortment Grapple does not require any special crane controls/extra joysticks. Instead, standard Nordic cut-to-length forwarder controls are used (Figure 2). The right joystick's rocker switch opens and closes the grapple as usual. When the conventional claws are opened maximally, the extra claws also open (Figure 1A). However, if the conventional claws are not opened maximally, the extra claws stay closed (Figure 1B). Both the conventional and extra claws close when the grapple is commanded to close. Hence, after the conventional claws have picked up the first pile, the extra claws close around this bundle and then the conventional claws can be opened again to pick up a second pile (Figure 1C). This feature enables the grapple to simultaneously hold two distinct piles.

The Assortment Grapple has previously been studied both in a machine simulator (Mörk et al. 2017) and in the field (Brunberg, Lundström 2016; Petaja et al. 2018). According to the field study by Brunberg and Lundström (2016), the number of crane cycles is reduced when the Assortment Grapple is used to load two assortments during a single crane cycle compared to loading only one assortment using a standard grapple. But because the loading of two assortments required extra sorting in the load-space and on the ground, no time was saved when the Assortment Grapple was used instead of the standard one. According to Brunberg and Lundström (2016), total time consumption when forwarding using the Assortment Grapple could even have been somewhat higher.

Petaja et al. (2018) chose a slightly different approach than Brunberg and Lundström (2016). In the field study by Petaja et al. (2018), the use of the Assortment Grapple was integrated with forwarding several assortments in a load. Meanwhile the use of the standard grapple was strictly limited to forwarding of single-assortment loads. According

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Figure 2. During the study, operators wore a virtual reality headset (brand Oculus Rift) which provided a 3-dimensional environment experience which is important during crane work. The Assortment Grapple does not require any special crane controls (i.e. joysticks), and standard controls, similar for all Nordic cut-to-length forwarders, are used

to Petaja et al. (2018), the working method linked to using the Assortment Grapple saves time during the loading work, but because of the larger number assortments, unloading takes more time. Petaja et al. (2018) did not find any significant difference in productivity between the compared work methods. So, Petaja et al. (2018) did not directly isolate the Assortment Grapple's effect on forwarding productivity but rather analysed it as a part of a classical trade-off, whether to forward single- or multi-assortment loads (c.f. Kellogg, Bettinger 1994; Nurminen et al. 2006; Manner et al. 2013).

Mörk et al. (2017) compared the Assortment and standard grapple in a machine simulator. In general, they did not find any difference in forwarding time consumption between the grapple types. But they found that the Assortment Grapple could possibly save time when two piles can be loaded during a single crane cycle given that no obstacles (remaining trees) exist between the piles. But if there exist any obstacles between the piles, a standard grapple appears to be more efficient. Mörk et al. (2017) also interviewed the operators who participated in their study. The operators experienced the Assortment Grapple's steering principals as rigid. Most importantly, the opening of the extra claws must be made more user-friendly. Moreover, Mörk et al. (2017) identified the need for clear guidelines. For example, under which circumstances should the Assortment Grapple's accumulating function be used to load two different assortments during a single crane cycle?

Objectives and hypothesis. The objectives of the present study were to: (*i*) formulate guidelines for working with the Assortment Grapple, and (*ii*) analyse its development potential. The hypothesis of the study was that the use of the Assortment Grapple decreases loading time consumption.

MATERIAL AND METHODS

Equipment and operators. To address the objectives of the study, we compared during 2018 the Assortment Grapple with a standard grapple in a machine simulator. During the study, operators wore a virtual reality headset providing a 3-dimensional environment (Figure 2). Such a 3-dimensional experience is important during crane work. The virtual forwarder used during the data gathering was based on a standard Komatsu 860.4 forwarder, and it had two pairs of extra stakes dividing the load-space into 3 sections. The forwarder was equipped with a crane based on the model Cranab CFR 11 (reach 7.9 m) and with a grapple which was based on a standard grapple by HSP Gripen (grapple area 0.28 m^2).

However, unlike Mörk et al. (2017), we did not use a virtual version of Helsinge Skog Innovation AB's standard pair of extra claws. Instead, we used a virtual version with slightly refined steering as according to the shortcomings reported by Mörk et al. (2017). Thus, in the present study, operators could open the Assortment Grapple's extra claws with a brisk grapple-open command regardless of the conventional claws' opening status. This improvement facilitates crane work because then the operator does not need to unnecessarily open the grapple maximally just to open the extra claws.

Four professional operators participated in the study. They were all male with ages ranging from mid 30s to early 60s and an average age of approximately 50 years. Their work experience of forwarding varied from ca. 10–30 years.

Experiment. The experiment was carried out using a standardised procedure. In this study, the operators did not reposition (drive) the machine at all. Instead, the machine was all the time correctly positioned in relation to the four piles to be loaded (Figure 3).

The loading of a pair of piles, consisting of one sawlog- and one pulpwood pile (containing 2 and 8 logs respectively), constituted a complete repeti-

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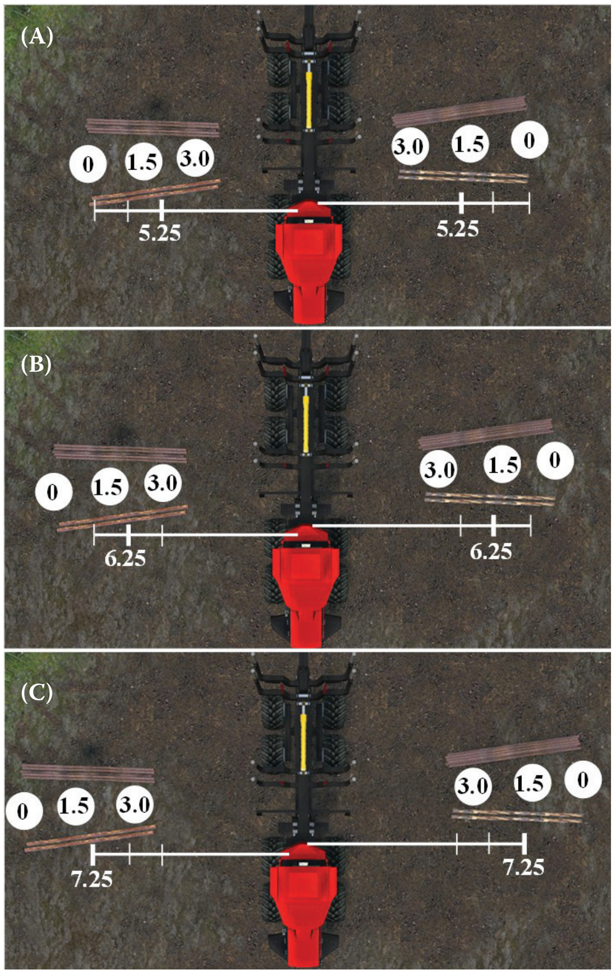

Figure 3. Bird's eye view of the experiment. Distance measured from middle point of each pile to the crane pillar was either 5.25 m (A), 6.25 m (B) or 7.25 m (C). An obstacle (hindering tree) was placed, irrespective of the applied distance, either 0 m (no obstacle), 1.5 m (intermediate) or 3.0 m (close) from the outer end of the piles

tion. Each repetition started with the grapple being inside the load-space (Figure 3). Irrespective of the grapple type, a repetition commenced when the grapple started to move towards the first pile on one side of the machine. But after grasping the first pile, the working method differed between the grapple types.

When using the standard grapple, the operator loaded the first pile singly in a predetermined assortment-specific section of the load-space. After that, he loaded the remaining second pile on that same side of the machine. The repetition ended when the second pile was placed in a predetermined section of the load-space. Then, the operator commenced a second repetition by repeating a similar work cycle on the opposite side of the forwarder. When all four piles had been loaded, the machine simulator's computer automatically created a new set of piles for the third and fourth repetitions, and so on.

When using the Assortment Grapple, the operator did not immediately load the first pile in the load-space but steered the grapple to the second nearby pile on that same side of the forwarder. Then using the extra claws, he grasped also the second pile, thereby holding two piles in the grapple. After that, the operator steered the grapple back to load-space and placed the piles in predetermined assortment-specific sections of the load-space. The operator then commenced a second repetition by repeating a similar work cycle on the opposite side of the forwarder. After that, the operator accomplished the third repetition and so on. The automatic process of replacing the already loaded piles with new ones was similar regardless of the grapple type.

The computer placed the log piles at one of the following three distances from the crane pillar: 5.25, 6.25 or 7.25 m (Figure 3). This distance was always kept constant during a given treatment. In addition, the computer placed a tree between the piles, either 0, 1.5 or 3.0 m from the outer end of the piles (Figure 3). This remaining tree became an obstacle at three different levels of proximity to the forwarder: close (3.0 m), intermediate (1.5 m) or none (0 m). The tree was placed midway between the sawlog and pulpwood piles (these two piles were always 1 m apart during the whole experiment). And again, the obstacle's proximity to the forwarder was always kept constant during a given treatment.

Originally, we suspected that the volume of logs in the load-space could affect the Assortment Grapple's relative benefit. Thus, as the computer replaced the old piles with new ones, it also adjusted the load-level. The load was either empty, pre-filled up to 30% or 70% of the stake height. Two repetitions were conducted sequentially with 0% load-level, two repetitions with 30% load-level, two repetitions with 70% load-level, and then again with 0% load-level and so on.

The same logs were used during the whole the experiment. The length of the logs was 450 cm. The sawlogs' and pulplogs' top diameters were approximately 15 cm and 10 cm respectively. But most importantly, the grapple (both conventional and extra claws) could easily accommodate the piles without any technical problem. The same goes for the crane, it could easily reach each pile.

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Each operator was allocated the machine simulator for one whole day. First, the operator trained using both grapple types. The time study was conducted after he felt familiar with the both grapple types. During the time study, operators repeated the assigned tasks (i.e. combinations of grapple type, distance, and obstacle) in predetermined order to neutralize any possible effect of learning curves (Björheden 2001). However, the number of repetitions varied slightly between the compared treatments. This variation arose from the removal of repetitions which were not conducted according to given instructions. The final dataset contained 1 504 observations in total. Group-wise numbers of repetitions are provided in the section "Results and Discussion".

We created a script using a MATLAB program (MathWorks Inc.) to collect data automatically. The script processed the data from the simulator. The script automatically identified repetitions and determined their time consumption based on the grapple's location, its opening-closing status, and the time elapsed since it was at a pile or in the load-space. This study comprised only pure loading crane work. All other forwarding work, i.e. driving empty, driving loaded, loading drive, and unloading, was excluded from the study.

Analysis of variance (ANOVA). There was only one dependent variable in this study, *Time consumption* per repetition, i.e. loading two piles. Meanwhile, there were four fixed factors: *Grapple* (levels: standard and Assortment Grapple), *Operator* (levels: A, B, C, D), *Obstacle* (levels: close, intermediate, none), and *Distance* (levels: 5.25, 6.25, 7.25 m). Hence, the levels of the four factors (*Grapple*, *Operator*, *Obstacle*, *Distance*) generated 72 treatments in total (2×4×3×3). Initially, *Load-level* was entered as covariate but then removed from the final statistical model because it did not affect residual behaviour. The design was balanced allowing a full factorial ANOVA including all possible interaction effects between the factors. Only productive machine time was included in the study (Björheden, Thompson 2000).

Least square means, i.e. estimated marginal means (EMM), medians, 5^{th} and 95^{th} percentiles were calculated for the treatments (Searle et al. 1980; Piepho, Edmondson 2018). The general linear model (GLM) was used to analyse the ANOVA model, and pair-wise differences were analysed using the Tukey-Kramer method. The significance level was set to 5%. Multiplicative inverse (reciprocal) transformation was used to meet the ANOVA assumptions. Only back-transformed EMMs are reported. Readers are referred to Table 1 in the section "Results and Discussion" for more detailed information on the final statistical model. Type III sums of squares (SS), i.e. partial sums of squares, were used to determine the proportion that the given term explained of the variance of the dependent variable. Enterprise Guide 7.1 (SAS Institute Inc.) was used for all statistical analyses. And finally, statistically significant differences between the grapple types are given as percentages derived using the following formula: 100% – "time consumption for the Assortment Grapple" / "time consumption for the standard grapple". Hence, positive signs denote time saved with use of the Assortment Grapple, while negative signs denote time lost.

RESULTS AND DISCUSSION

All analysed terms with two exceptions (*Operator* × *Obstacle* and *Grapple* × *Distance* × *Obstacle*) had a significant effect on the dependent variable *Time consumption*$^{-1}$ (Table 1). According to Type III SS, the most important factors were *Obstacle* and *Distance*, and these factors explained 19.2% and 17.2% of the total variation in the dependent variable *Time consumption.*

Grapple types compared over the distance and obstacle proximities with operators pooled

When grapple types were compared across the distances and obstacle proximities, significant differences between the grapple types were found only when no obstacle at all existed (Table 2). In the case of no obstacle, the relative time saving when using the Assortment Grapple increased with increasing distance (9.9%, 12.3% and 16.4%, Figure 4).

When the data was pooled also across the factors *Distance* and *Obstacle,* time consumption when using the Assortment Grapple and standard grapple was 14.7 and 15.5 seconds, respectively. This time saving of 5.0% with the Assortment Grapple was significant ($P < 0.001$, no table data shown).

For both grapple types, time consumption increased significantly with increasing distance ($P < 0.001$, no table data shown). However, the *Distance*-factor had a stronger effect on time consumption when using the standard grapple. This fact resulted in a significant interaction effect, *Grapple* × *Distance* (Table 1).

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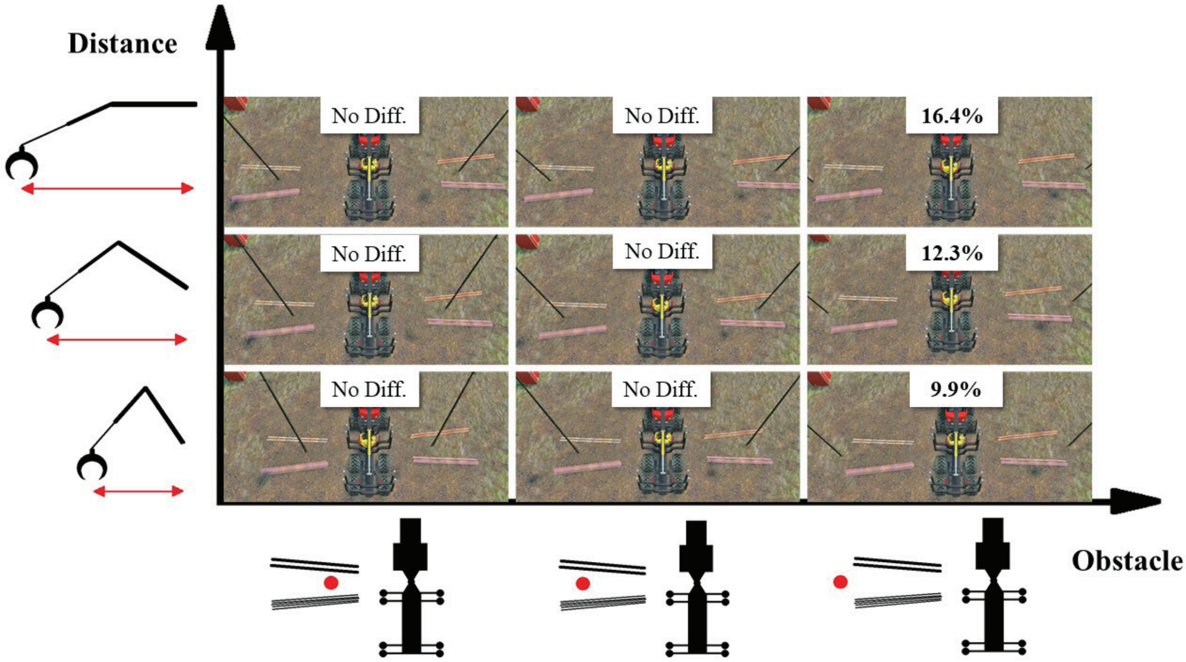

Figure 4. Statistically significant time savings when loading log piles with the Assortment Grapple at three distances and three obstacle proximities compared to a standard grapple ($P < 0.001$, operators pooled). No Diff. = no significant difference in time consumption between the two grapple types ($P > 0.05$). More detailed numerical analyses shown in Table 2

When using the Assortment Grapple, time consumption increased significantly with increasing obstacle proximity ($P < 0.001$, no table data shown). The same went for the standard grapple, with exception of obstacle levels "none" and "intermediate" which did not differ significantly from each other ($P = 0.756$, no table data shown). Thus, the effect of *Obstacle* varied between the grapple types resulting in a significant interaction effect, *Grapple* × *Obstacle* (Table 1).

Table 1. Levels of significance (*P*-values) and Type III sums of squares (SS) obtained from the analysis of variance (ANOVA). The dependent variable is *Time consumption*$^{-1}$. The number of observations was is 1 504. Explained variance by the model was 64.4% ($P < 0.001$)

Term	Type III SS	*P*-value
Grapple	0.00426	< 0.001
Operator	0.00448	< 0.001
Distance	0.02115	< 0.001
Obstacle	0.02360	< 0.001
Grapple × *Operator*	0.00936	< 0.001
Grapple × *Distance*	0.00033	< 0.01
Grapple × *Obstacle*	0.00755	< 0.001
Operator × *Distance*	0.00076	< 0.001
Operator × *Obstacle*	0.00037	0.060
Distance × *Obstacle*	0.00053	< 0.01
Grapple × *Operator* × *Distance*	0.00101	< 0.001
Grapple × *Operator* × *Obstacle*	0.00211	< 0.001
Grapple × *Distance* × *Obstacle*	0.00015	0.291
Operator × *Distance* × *Obstacle*	0.00217	< 0.001
Grapple × *Operator* × *Distance* × *Obstacle*	0.00152	< 0.001

Operators' responses to the grapple types

The data was operator-wise pooled across the factors *Distance* and *Obstacle*, and the four operators' (A, B, C, D) responses to the grapple types were compared individually. Operators A and B saved time when using the Assortment Grapple, 11.1% and 12.1%, respectively ($P < 0.001$, $n = 352$ and 372, no table data shown).

In contrast, operator C consumed 4.5% more time when using the Assortment Grapple ($P < 0.001$, $n = 391$, no table data shown). Meanwhile, no significant difference was found between the grapple types for operator D ($P = 0.676$, $n = 386$, no table data shown).

Detailed intra-operator comparisons also supported the results from the operator-pooled analyses (c.f. Table 2 and 3). Compared to the standard grapple, no operator lost time using the Assort-

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Table 2. *Time consumption* in seconds to accomplish the given task as according to the factors *Obstacle*, *Distance* and *Grapple* (with operators pooled). Estimated marginal means (EMM) are followed by medians, and 5th and 95th percentiles in parentheses. Positive differences (%) denote time savings when using the Assortment Grapple. Negative differences denote time lost. *n* is the number of repetitions

Obstacle	Distance (m)	Standard grapple			Assortment Grapple			Difference
		EMM	Median (5th; 95th)	*n*	EMM	Median (5th; 95th)	*n*	
Close	5.25	15.4	15.5 (13.6; 18.1)	84	15.8	15.5 (13.5; 19.8)	80	$P > 0.05$
	6.25	15.8	15.7 (14.3; 18.2)	82	16.1	15.9 (14.4; 19.1)	85	$P > 0.05$
	7.25	17.6	17.7 (15.5; 21.0)	83	17.3	17.1 (15.3; 20.9)	76	$P > 0.05$
Intermediate	5.25	14.3	14.1 (12.8; 16.8)	90	14.1	13.9 (12.1; 17.5)	89	$P > 0.05$
	6.25	14.8	14.8 (13.1; 17.7)	77	14.6	14.2 (12.7; 17.4)	75	$P > 0.05$
	7.25	16.7	16.9 (15.2; 19.4)	76	16.3	16.1 (14.0; 19.9)	98	$P > 0.05$
None	5.25	13.9	13.9 (12.0; 16.7)	96	12.6	12.4 (10.9; 16.3)	82	9.9%***
	6.25	14.8	14.9 (13.0; 16.5)	78	13.0	12.9 (11.2; 15.8)	82	12.3%***
	7.25	16.7	16.8 (14.5; 19.3)	84	14.0	13.8 (12.1; 17.5)	88	16.4%***

***$P < 0.001$; complete ANOVA-model and results are presented in Table 1

ment Grapple when the loading work was free of obstacles (Table 3). Indeed, operators A, B and D rather saved time, 20.7%, 20.0% and 8.5% respectively (Table 3). Meanwhile, no significant difference between the grapple types was found for operator C (Table 3). A lack of working routine when using the Assortment Grapple is one potential reason why operator C did not benefit from the Assortment Grapple. Hence, we infer that the results for operator C could have been better when using the Assortment Grapple if he had practiced even more with it.

Strengths and weaknesses of the study

The work element "unloading" was not included in our study. However, there is no reason to assume that the loads' structure or log arrangement differed between the grapple types because the same logs were placed similarly in predetermined positions in the load-space irrespective of grapple type.

Table 3. *Time consumption* in seconds to accomplish the given task as according to the factors *Operator*, *Obstacle* and *Grapple* (with distances pooled). Estimated marginal means (EMM) are followed by medians, and 5th and 95th percentiles in parentheses. Positive differences (%) denote time savings when using the Assortment Grapple. Negative differences denote time lost. *n* is the number of repetitions

Operator	Obstacle	Standard grapple			Assortment Grapple			Difference
		EMM	Median (5th; 95th)	*n*	EMM	Median (5th; 95th)	*n*	
A	close	16.1	15.7 (14.3; 18.5)	54	15.5	15.3 (14.5; 16.7)	59	3.8%***
	intermediate	15.1	14.8 (13.8; 16.8)	60	14.1	13.6 (12.5; 16.3)	60	6.6%***
	none	15.5	15.2 (13.8; 17.9)	60	12.3	12.4 (10.9; 13.8)	59	20.7%***
B	close	16.4	16.5 (14.2; 19.3)	65	15.8	15.8 (13.2; 18.4)	64	$P > 0.05$
	intermediate	15.9	15.8 (13.6; 20.1)	59	14.2	14.5 (12.0; 17.6)	63	10.7%***
	none	15.6	15.3 (13.0; 19.3)	60	12.4	12.3 (11.1; 14.2)	65	20.0%***
C	close	16.9	16.7 (15.0; 19.9)	70	17.4	17.1 (15.2; 20.9)	58	$P > 0.05$
	intermediate	15.1	14.8 (13.3; 18.1)	59	16.6	16.7 (14.0; 20.0)	69	–10.4%***
	none	14.4	14.6 (11.9; 17.2)	66	14.5	14.6 (11.9; 17.6)	69	$P > 0.05$
D	close	15.4	15.2 (13.3; 19.0)	60	17.0	16.9 (14.8; 20.7)	60	–10.1%***
	intermediate	14.9	14.4 (12.8; 17.8)	65	15.1	15.3 (12.5; 19.7)	70	$P > 0.05$
	none	14.9	15.0 (12.6; 17.9)	72	13.7	13.6 (11.7; 16.9)	59	8.5%***

***$P < 0.001$; complete ANOVA-model and results are presented in Table 1

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Moreover, the extra claws are typically not used during unloading; consequently, unloading work with the Assortment Grapple does not differ from unloading with the standard grapple.

Also, the work element "loading-drive" was excluded from the study. This exclusion might have slightly favoured the Assortment Grapple. When using standard grapples, operators have in reality the possibility to simultaneously load piles and drive (slowly) to increase productivity. Simultaneous loading and driving might be more difficult when using the Assortment Grapple to load several piles during a single crane cycle. However, the remaining trees in thinnings make simultaneous crane work and driving difficult and therefore this weakness might only be theoretical. Loading-drive was excluded from the study to simplify the work so that the study participants could in short time assimilate it. On the other hand, the operators' previous work experience was from using the standard grapple. This fact could have favoured the standard grapple despite our actions to accelerate the learning curves and the assimilation of new work methods.

Scientific studies on harvester work carried out in a machine simulator have been published occasionally (e.g. Ovaskainen 2005; Ovaskainen et al. 2011; Dvořák et al. 2016). But similar studies on forwarding are rare/non-existent. We discovered that machine simulators can be an applicable alternative for scientific studies also on forwarding because causal relationships are easy to establish. The simulator's ability to isolate the grapple type's effect on time consumption could be one reason for why our results differed slightly from those of previous studies like Brunberg and Lundström (2016) and Petaja et al. (2018).

CONCLUSION

Guidelines for working with the Assortment Grapple

In general, we recommend that operators use the assortment-handling function of the Assortment Grapple only when the grapple can be steered from the first to the second pile without there being any obstacles (remaining trees) between the piles. In such cases, none of the operators participating in this study lost time, and three of four operators saved time notably. However, this general guideline is perhaps a bit conservative, because this study has shown that skilful operators benefit from the Assortment Grapple even when moderate obstacles occur.

The Assortment Grapple's development potential

The use of the Assortment Grapple is most efficient when there are no remaining trees between the piles to be loaded during the same crane cycle. The problem with these remaining trees is that extra time is required when steering bunches of logs around them. However, using a "tilt-grapple" together with the Assortment Grapple could perhaps reduce the extra time required. The tilt-grapple enables a bunch of logs to be tilted vertically into an upright position, which means that they can be steered more easily around remaining trees during the loading-crane cycles (Häggström et al. 2016; Kaleja et al. 2018).

Harvester operators can facilitate the use of the Assortment Grapple by placing log piles in the same space with no remaining trees between them. Hence, harvester and forwarder operators should plan the thinning operation jointly before starting work.

Despite the enhanced steering principals, the usability of today's Assortment Grapple could be further improved. Currently, the extra claws do not have their own switch since the right rocker switch controls both the conventional and the extra claws. This solution is technically simple but not particularly user-friendly. The Assortment Grapple's extra claws should instead be controlled by their own switch.

Thus, the results partly confirmed the hypothesis; the Assortment Grapple has a notable potential to decrease loading time consumption, but the decrease is dependent on how the harvester operator places the piles.

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