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Influence of Loading Distance, Loading Angle and Log Orientation on Time Consumption of Forwarder Loading Cycles: A Pilot Case Study

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Abstract: Fully mechanized timber harvesting systems are well established in forest operations worldwide. In cut-to-length (CTL) systems, forwarders are used for extracting logs from the stand. The productivity of a forwarder is related to site- and stand-specific characteristics, technical parameters, organizational aspects, and the individual skills of the operator. The operator's performance during "loading" considerably affects forwarder productivity, since this element occupies nearly 50% of forwarding cycle time in CTL operations. When positioning the forwarder for loading, different loading angles and loading distances arise. Additionally, different log orientation angles in relation to the machine operating trail can be observed. Therefore, an in-depth analysis of loading conditions was conducted. The goal of this pilot case study was to explore the potential impact of different loading angles and distances, and log orientation angles, on time consumption per loading cycle in order to derive indications for more efficient work practices. Therefore, controlled loading sequences were tested on a physical Rottne-F10-based forwarder simulator with an experienced forest machine operator. Three loading angles (45°, 90° and 135° azimuthal to the machine axis) with five loading distances (3, 4, 5, 6 and 7 m), and three log orientation angles (45°, 90°, 135°), resulted in a total of 45 settings, which were tested in 10 repetitions each. The time required for a loading cycle was captured in a time study, applying the snap-back method. Results showed that all three tested variables had a significant influence on time consumption per loading cycle. Loading at an angle of 135°, and from a close (3 m) or far distance (7 m) led to especially increased cycle times. Loading from 4 to 6 m distance could be detected as an optimal loading range. Additionally, log orientation angles of 45° and 90° led to increased loading efficiency. Even if the validity of the results may be limited due to different conditions and influencing factors in field forwarding operations, these data can contribute to a better understanding of the loading element and, in particular, to productivity determining factors of forwarder work.

Keywords: forest engineering; forest operations; cut-to-length; time and motion study; forwarding; hydraulic loader; machine operator

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1. Introduction

Fully mechanized timber harvesting using single grip harvesters and forwarders (cut-to-length method) is commonly applied in forestry in many parts of the world [1] due to its high productivity [2] and high occupational safety [3]. In Germany, between 50 and 60% of the timber is felled and processed by harvesters [4–7], which results in lower amounts of damages to the remaining stand as compared to motor-manual felling [8]. Commonly, a forwarder extracts the logs cut and placed along the machine operating trail by the harvester and piles them at the landing, situated along forest roads that can be accessed by logging trucks [9]. The productivity of a harvester depends largely on the characteristics of the forest stand and terrain [10]. Forwarder productivity is also influenced by diverse factors affecting all work elements. However, the in-depth consideration of individual work elements in productivity studies is less pronounced for forwarder work compared to harvester work.

Factors influencing forwarding productivity in CTL systems include: (I) operator-related parameters (i.e., skills and experience [11–14]), which are also related to preceding harvester work, such as pre-bunching and separation of assortments, the positioning of logs and also the concentration of logs along machine operating trails [1,9,15,16]; (II) stand and timber characteristics such as the stem volume [17] or the number of assortments [15,18–20]; (III) terrain-related factors such as slope [21,22] or the extraction distance [16,19–23]; (IV) technical parameters such as the loading capacity of the machines used or track support [16,20,23]; and (V) general organizational aspects [24], such as the harvested volume per area [19], and, in this context, the total harvesting volume [10] or restrictions related to forest management [25,26], e.g., silvicultural objectives [27]. Indirectly, even the frequency of maintenance influences productivity as it affects the duration of downtime [28]. It should be noted that some of these determinants of forwarder productivity cannot always be clearly assigned to one of the categories mentioned above. However, these factors are all capable of influencing the performance and productivity of a forwarder in operation.

All in all, forwarder work can be divided into four work elements: *loading*, *unloading*, *driving empty*, and *driving loaded* [15,29]. Of the total forwarding cycle time, 45% and more can be assigned to the loading element [9,15,21,30] and operating the boom can occupy nearly 75% of the loading element itself [30]. The work method forest machine operators apply in crane work strongly affects productivity [31]. Such findings suggest further analyses of the loading work element.

When focusing on work elements and harvester-forwarder interactions in CTL operations, it has been shown that the placement and therefore concentration of logs caused by preceding harvester work also influences productivity [9,15]. In most cases, the processed logs are placed at the edge of the machine operating trail, usually lying at a slightly varying azimuthal angle to the longitudinal axis of the trail [9]. Depending on the positioning of the forwarder when loading, variable loading distances to the crane pillar, as well as variable loading angles to the bunched log assortments, can be observed. The angular orientation of the logs in relation to the machine varies according to the direction that the forwarder drives through the stand.

The study presented in this article was designed and conducted in order to contribute towards a better understanding of the loading work element and to derive additional recommendations to best practice work methods for forwarding operations. The overall goal was to quantify the influence of the loading angle, the angular orientation of logs, and the loading distance on the time consumption of forwarder loading cycles. Therefore, the study concentrated on controlled loading conditions under exclusion of other factors affecting forwarder productivity, allowing for a detailed analysis of the "loading element".

2. Materials and Methods

2.1. Machine

The study was carried out in cooperation with the Lower Saxony State Forest Service (Niedersächsische Landesforsten) at the Forest Education Center in Münchehof near Seesen in Lower Saxony, Germany. For the training of forest machine operators, the Forest Education Center uses physical forwarder simulators built from production components of a regular Rottne F10 forwarder (Figure 1, see Table 1 for technical details). They consist of an operator's cabin, a load space and a Rottne RK 85 crane. The simulator used in this study differs from a real Rottne machine in two respects. Firstly, the simulator is mounted on a stationary base instead of a wheeled undercarriage. Secondly, instead of an internal combustion engine, the hydraulics are powered by an electric motor. All other components are identical.

Figure 1. Rottne-F10-based forwarder simulator used in the study.

Table 1. Specifications of the Rottne RK 85 crane.

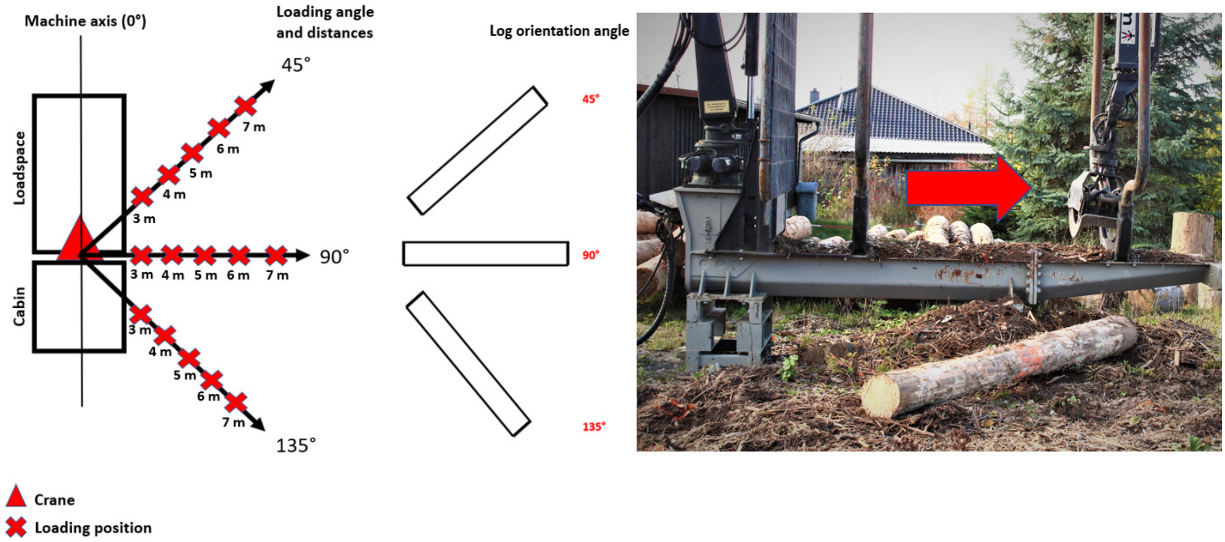
Crane Type	RK 85
Maximum reach	7.5 m
Lifting torque, gross	86.7 kNm
Lifting capacity at 7.5 m	730 kg
Lifting capacity at 4.0 m	1490 kg
Slewing torque	27.1 kNm
Angle of rotation	380°
Tractive force	18 kN

2.2. Study Setup

Using the simulator, a study design with the aim of facilitating standardized, repeatable execution of forwarder loading sequences was set up. Five different loading distances (i.e., distances between crane pillar and the center of a log) were simulated on flat terrain (3 m, 4 m, 5 m, 6 m and 7 m, Figure 2a). Each of these loading distances was tested in combination with three different loading angles (45°, 90°, and 135° azimuthal to the machine axis, Figure 2a). Additionally, three different log orientation angles were simulated for each loading position (45°, 90°, and 135° azimuthal to the longitudinal axis of the machine, Figure 2b). Overall, this testing design resulted in 45 individual settings, i.e., combinations of loading distances and angles and log orientation angles. Each setting was tested with 10 repetitions to record a total of 450 loading cycles. Loading angles, log orientation angles and loading distances were measured from the center of the crane pillar using a compass and a measuring tape, respectively.

2.3. Elemental Time Study and Operator

The fixed starting position of the closed grapple at the beginning of each loading cycle was located at the back of the load space, as shown in Figure 2c. Cycle time measurements started when the boom was moved from its fixed starting position and stopped when the log was positioned at the front of the load space. Following a timed loading cycle, the machine operator was required to place the log back to the predefined loading position and move the boom back to the starting position, ready for the next cycle to begin. The time of each cycle was manually measured in hundredths of a second using a stopwatch. The loading position on the ground was marked with spray paint and was regularly renewed due to the increasingly poor visibility of the markings between the loading cycles caused by the loading process. The log used had a length of 3 m and a mid-diameter of 27 cm (0.17 m^3). The gripping point was predefined as the middle of the log and also marked with spray paint. For data backup, parallel video recordings of all loading cycles were made with a Sony HC-V777 camera.



(**a**) (**b**) (**c**)

Figure 2. Study setup: (**a**) loading distances and loading angles; (**b**) different log positions; and (**c**) start position of boom before loading cycles.

It was critical for the validity of this loading work study that the test operator had sufficient experience in forwarder work (especially loading). Therefore, a forest machine operator instructor at the Forestry Training Center (male, aged 41 at the time of the study) with 20 years of experience operating forest machines, both harvesters and forwarders, was selected as the test operator. Before working on forest machines, the test operator completed a dedicated training program for forest machine operators. Sufficient skill and experience were confirmed since the test operator regularly trains participants of forest machine operator training programs on the training center's simulators. Since project funds were limited and additional operators were not available, conducting the experiment with several test operators was not possible. Therefore, a test operator with a high level of skill needed to be selected. The overall goal was to create controlled conditions for the test operator in the form of standardized motion sequences. It was assumed that the lack of performance pressure in the study would contribute to an optimal motion sequence for the test operator. Regarding the objectives of the study, the methods were selected to allow for a detailed study of the loading element, whereas a comparison of operators was not intended.

2.4. Statistical Analysis

All study parameter combinations resulted in a total of 450 recorded loading cycles. The balanced data was analyzed using the free software language R (version 4.0.2, [32]), interfaced with RStudio (version 1.4.1103, RStudio, PBC, Boston, MA, USA). In order to receive normally distributed residuals of the linear model applied, measured values of time consumption were transformed into reciprocal values. These were used and fitted by a linear model using generalized least-squares {package: nlme}. A constant variance function ('varIdent', {package: nlme}) was used for the factor loading angle, to consider the heteroscedastic distributions among this factor. Normal distribution of the residuals was tested and confirmed by means of a Shapiro-Wilk test. The independent factors loading angle, distance and log orientation were used, including all possible interactions. Least-square means were estimated using the package {emmeans}, where the reciprocal response values were back-transformed to reveal time consumption in seconds. Pairwise comparisons were conducted between each setting {package: multcomp} using Tukey's

HSD test. The significance level for all tests was set at $\alpha = 0.05$, and least-square means are given with their standard error (SE) and confidence limits for a 95%-interval.

3. Results

An average time consumption of 16.6 ± 3.02 s (±SD) was required to accomplish a loading cycle. Means per operational setting surveyed ranged between 13.4 ± 0.303 s and 23.2 ± 0.912 s. The analysis showed that all considered independent variables (loading angle, loading distance, and log orientation) had a significant influence on the reciprocal values of time consumption per loading cycle. Interactions between loading angle and loading distance, as well as loading angle and log orientation, were found to be significant. The interaction between loading distance and log position was not found to be statistically significant ($p = 0.2245$), but the 'full' model showed a higher coefficient of determination, compared to a reduced factorial model. Thus, analyses including all variables and possible interactions were carried out. The highest share of variance in the data could be explained by loading angle, followed by log orientation, and then loading distance, according to decreasing *F*-values (Table 2).

Table 2. Analysis of variance of the linear model (using generalized least-squares), fitted to reciprocal values of time consumption required for loading (L.) cycles of a forwarder.

	numDF	*F*-Value	*p*-Value
(Intercept)	1	60,436.19	<0.001
L. Angle	2	357.59	<0.001
L. Distance	4	47.17	<0.001
Log Orientation	2	56.31	<0.001
L. Angle: L. Distance	8	4.79	<0.001
L. Angle: L. Orientation	4	7.22	<0.001
L. Distance: Log Orientation	8	1.33	0.225
L. Angle: L. Distance: Log Orientation	16	3.71	<0.001

3.1. Influence of Loading Angle on Time Consumption Per Loading Cycle

Significant differences could be observed between loading angle, whereas least-squares means of the back-transformed response variable increased from 14.6 s per loading cycle for a loading angle of 45° to 15.3 s for a loading angle of 90° and to 19.0, when loading was carried out at an angle of 135°, respectively. Least-squares means of time consumption required for loading cycles for each group of loading angle tested are given in Table 3.

Table 3. Least-squares means of time consumption required for loading cycles for each group of loading angle tested.

Loading Angle [°]	Estimated Mean Time Consumption	SE	df	Lower CL	Upper CL	Group
45	14.6	0.094	405	14.5	14.8	a
90	15.3	0.102	405	15.1	15.5	b
135	19.0	0.157	405	18.7	19.3	c

3.2. Influence of Log Orientation on Time Consumption Per Loading Cycle

Differences in time consumption due to log orientation were lower when compared to the effect of loading angle, with least-squares means ranging from 15.3 to 17.0 s per loading cycle, pooled across the independent variables loading distance and angle. The estimated mean time consumption per loading cycle for each log orientation is given in Table 4.

Table 4. Estimated mean time consumption per loading cycle for each log orientation.

Log Orientation [°]	Estimated Mean Time Consumption	SEM	DF	Lower CL	Upper CL	Group
45	15.3	0.102	405	15.1	15.5	a
90	16.1	0.114	405	15.9	16.3	b
135	17.0	0.126	405	16.7	17.2	c

The analysis showed that time consumption per loading cycle increased with higher log orientation angle at all three loading angles. Still, the rates of increasing time consumption with higher log orientation angle differed between the three loading angles. Different lower-case letters indicate significant differences between different log orientation angles within a loading angle according to Tukey´s HSD test (as seen in Figure 3).

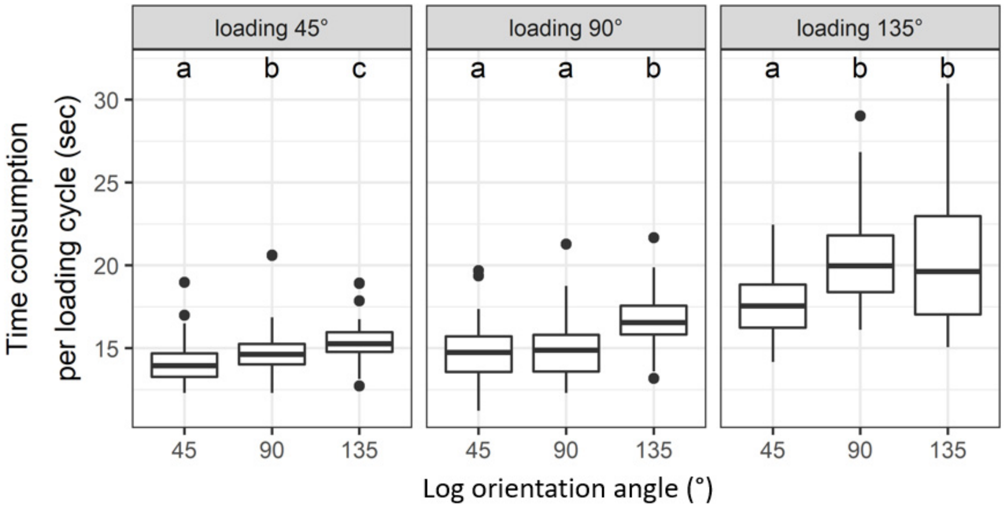


Figure 3. Distribution of time consumption per loading cycle for three log orientation angles and three loading angles.

3.3. Influence of Loading Distance on Time Consumption Per Loading Cycle

While time consumption increased with increasing loading angle and log orientation, different loading distances resulted in a more specific influence on time consumption per loading cycle. The data indicated that the smallest distance between the crane and the position of the log did not reduce the time required to load the logs. The closest proximity of a log, at a distance of 3 m from the crane pillar, resulted in higher time consumption per loading cycle, compared to distances of 4 m, 5 m, or 6 m (Table 5). The estimated mean time consumption for the closest distance of 3 m was similar to values reached at the maximum distance of 7 m.

Table 5. Least-squares means of time consumption required for loading cycles of each loading distance.

Loading Distance [m]	Estimated Mean Time Consumption	SE	df	Lower CL	Upper CL	Group
3	17.0	0.163	405	16.7	17.3	a
4	15.0	0.128	405	14.8	15.3	b
5	15.4	0.133	405	15.1	15.6	b
6	15.9	0.143	405	15.6	16.2	c
7	17.4	0.170	405	17.0	17.7	a

These patterns could be observed for all three loading angles, whereas ranges between mean values for each distance differed. Groups with dissimilar lower-case letters indicate significant differences according to a Tukey-HSD post hoc test (Figure 4). The significant interaction between loading angle and loading distance indicated that the loading distance had a stronger effect on time consumption when loading at greater angles. Accordingly, the loading angle of 45° revealed the lowest differences between groups of loading distance, with corresponding mean values of time consumption per loading cycle ranging from 14.0 (4 m) to 15.4 s (7 m). Differences in time consumption increased when loading was carried out at a loading angle of 135°. At 135°, least-squares means differed by 3.99 s between groups for a loading distance of 7 m and 3 m, compared to a smaller difference of 1.45 s at a 45° loading angle.

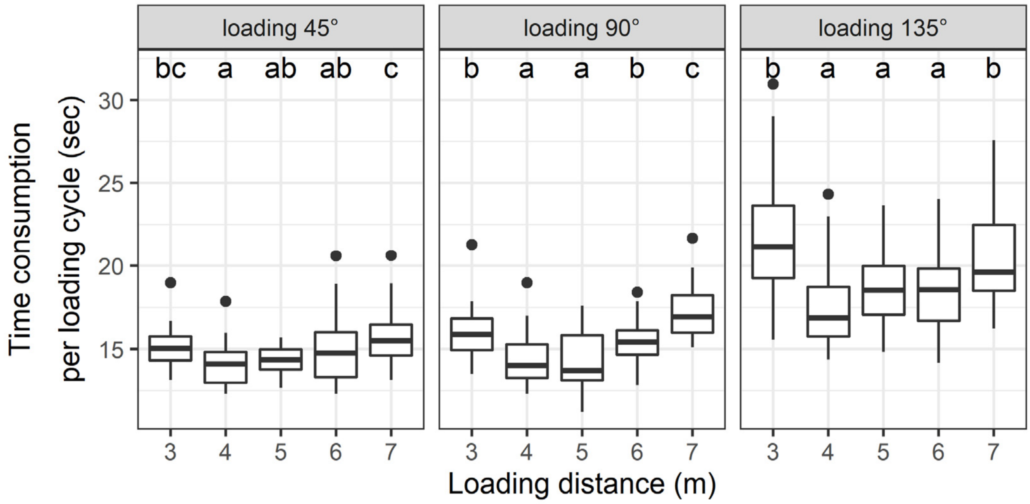


Figure 4. Boxplots showing time consumption per loading cycle for five different loading distances (m) and three different loading angles (°).

3.4. Increase of Time Consumption Per Loading Cycle According to Test Settings

Potential efficiency degradations or -improvements during the loading sequences performed were influenced by all three independent variables investigated in this study. In addition to these variables, the complexity of the measured work element was reflected by significant interactions between the surveyed variables (Table 2). Figure 5 shows estimated differences of time consumption for the entirety of the 45 variable combinations surveyed. The reference value (0% increase of time consumption) was 13.3 s per loading cycle. The remaining settings led to various increases of time consumption, and in return to decreased efficiency. Relative differences found to be significant in pairwise comparisons between the reference of 13.3 s and every remaining setting are indicated by the '+' in Figure 5.

Considering the significant increases of time consumption, the loading angle of 135° resulted in the least efficient loading cycles, at all three levels of log orientation angle and most pronounced for the shortest and longest loading distances.

Overall, the lowest time consumption values occurred at a distance of 4 and 5 m, when the operator loaded the logs at an angle of 45° or 90°, and logs were positioned at an angle of 45° or 90°. The corridor of low time consumption seemed to be narrow, surrounded by areas of severe shortfalls in efficiency (Figure 5). Under a loading angle of 135°, averages of increasing time consumption ranged between 40% and 75%.

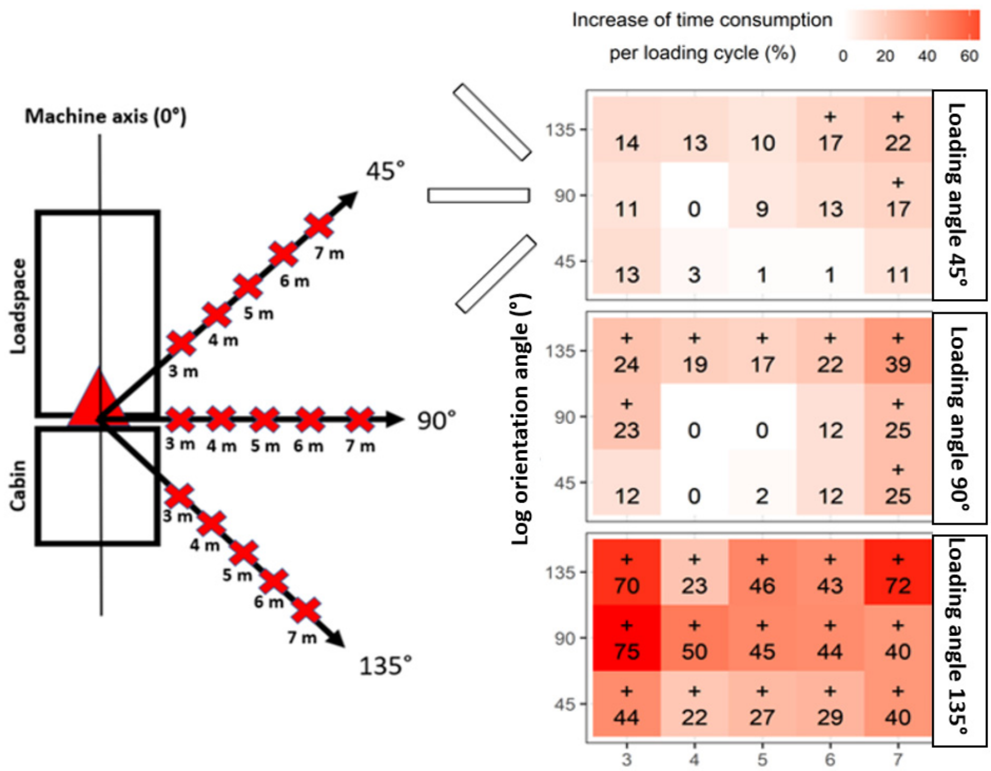


Figure 5. Relative increase of time consumption for loading cycles according to all test settings and reference value ('0').

4. Discussion

4.1. Methodology

The present study setup was chosen to explore the influence of loading angle, loading distance and log orientation angle on time consumption per loading cycle. Therefore, the executed loading sequences had to be standardized and repeatable. The selected test layout allowed for assessing multiple combinations of the analyzed factors covering many of situations occurring in reality. However, the study design focused on these factors and was not set up for quantifying additional factors influencing time consumption of forwarders loading cycles, such as slope or the forwarding distance. The setting of controlled conditions for an in-depth analysis of loading angle, loading distance and log orientation angle does therefore not allow generalized statements with respect to the influence of the tested factors on time consumption per loading cycle in a "real-world" operation. However, the results of the present pilot study show that there is at least a significant influence of all tested variables on loading time. How intense this influence is in field operations cannot be determined by the chosen setup.

The question arises whether the test setup represented real-world loading procedures. In general, it has to be taken into account that the sequence and motions carried out by the operator differ from a regular loading task. Therefore, results can just serve as an excerpt. However, the results could still help in analyzing the loading element, as variability in loading angles, distances, and log orientation angles also occurs in practice, commonly [9]. The methodology did not consider obstacles such as remaining trees, which probably affect time consumption per loading cycles [33]. Certainly, the present study cannot cover the variety of loading conditions. Therefore, the methodology is only able to provide an insight in the significance of selected factors.

A potential weakness of the study may be the fact that a simulator was used instead of a real machine. However, the simulator differs from a real machine in just two aspects (no wheels, electronic motor). The core components of the simulator resemble physical Rottne forwarders and therefore, for example, crane speed and -dimensions are the same.

Studies revealed that operator´s working technique on simulators and real machines is nearly the same [34]. To sum up, the simulator used is not fully capable to reproduce real world forwarding operations, but for in-depth analyses of the loading element, there is no difference to "real" machines. Since other factors such as obstacles while loading or slope weren´t considered in the analysis, results of the work study methodology should not be generalized, but provide insight in factors influencing loading time and performance within the loading work element [35].

Additionally, the predefined gripping point on the logs could have introduced a small systematic bias. During exercise cycles, when the gripping point on the log was not predefined, the loading cycle duration was generally slightly lower than during the loading cycles forming the data basis of this study. After evaluating the video material, it was also found that by predefining the gripping point, the machine operator sometimes marginally corrected the position of the boom tip to grip in the marked zone. It has to be expected that minor time savings could result from a free choice of the gripping point on the log. The operator usually does not grip the log in the middle, but closer to the one of the ends. In this way, one end of the log always hangs down slightly, allowing for easier placement against the front grate of the load space.

The grapple position at the beginning of each loading cycle was also predefined. Due to this position at the back of the load space, the machine operator did not reach through the stakes. However, due to the crane geometry and the structure of the load space, it was difficult to position the boom tip centrally in the load space. The machine operator would have had to intensively adjust the main boom and stick to get the boom tip out of the load space efficiently. In reality, when driving to the next log assortment between loading processes, it is also common to position the boom tip at the front of the load space on top of the logs. Therefore, this grapple position would have been the most practical for the machine operator. However, it can be assumed that the different grapple position at the beginning of the loading cycles in this study influenced the time consumption.

It is also important to note that it was not possible to consider loading from both sides of the machine with the presented study setup due to immobile obstacles on the other side. When loading with forwarders in mechanized CTL logging operations, it is most often necessary to load from both sides. It is possible that forest machine operators have individual preferences leading to higher or lower time consumption per loading cycle depending on the side.

It further needs to be considered that the operator worked with one log. Usually, it can be assumed that forest machine operators try to fully utilize the capacity of the grapple. But due to the character of this study it was decided to use one log only. Therefore, the results cannot support any statement on how a varying load in the grapple affects time consumption per loading cycle. However, additional tests with full grapples showed that patterns and interactions of tested factors in time consumption of different loading angles, distances and log orientation angles are similar, but have a higher absolute time consumption when loading more than one log.

One limitation of the study is that only one operator was tested. In a nutshell, no statement can be made about the extent to which other operators would have deviated in absolute and relative terms from the patterns found in this study. Other studies have shown strong differences in productivity between operators [36,37]. According to a long-term study, productivity differences of up to 37% can be explained by an operator effect [38]. Therefore, results need to be differentiated, as differences between operators could not be shown with the present setup, and these often are key elements of productivity in CTL systems [14,39]. However, a preliminary trial conducted in the context of this study using a different machine operator showed similar results, although higher absolute time consumptions were recorded. By choosing a forest machine operator with many years of experience operating forwarders, an attempt was made to reduce any influence of insufficient experience of the operator. The low variance of the time consumption for the loading cycles generally observed might indicate a high level of experience of the operator. Additionally, it was not the objective of this pilot study to compare the performance of different machine operators, but to conduct a work study to describe as detailed as possible patterns while loading, the influence of different loading angles, loading distances and log orientation angles, and related regularities in an explorative manner. Further research should aim for performance comparisons of, for example, more or less experienced operators.

In conclusion, the design used in the present study only serves as a snapshot and cannot represent the variety of factors that have an impact on the productivity of a forwarder, also due to the fact that the unloading work element was not tested. However, the design is easily adaptable and could show some productivity determinants of the forwarder loading element in mechanized CTL timber harvesting, even if the methodology is not able to quantify the absolute influence of the tested variables in real world scenarios. Further investigations in regular forwarding operations are ongoing, already, and respective insights will follow.

4.2. Influence of Loading Angle on Time Consumption

Results showed significant differences in time consumption per loading cycle between all loading angles tested. On the one hand, this could be explained by the crane tip paths, with their length being a function of loading angle and distance. Additionally, since the machine did not have a rotating cabin, the test operator usually positioned the seat diagonally forward in order to also view the load space while loading. In this case, reaching for the 135° loading angle meant that the operator had to turn his head considerably and crane functions were actuated with a delay or interrupted.

Another problem with loading from the 135° angle which is also linked to loading distance, could be the distance of the logs to the operator, not to the crane pillar. As some of the loading positions (3 and 4 m) at the 135° angle were close to the operator cabin, the end and middle of the log could not always be seen by the operator. As a result, the machine operator had to carefully pull the logs out of these positions with the boom tip, before returning to common loading speed. The video analysis has shown that movements at the 135° loading angle were performed much more smoothly when not only the middle but also the end of the log were visible. Since the differences in time consumption between the 45° and 90° angles were only minor, it would have been interesting to test the intermediate range between 90° and 135°.

The increasing time consumption when loading at a 135° angle could also partly result from the fact that the crane speed is increasing with longer crane paths. As a result, a more abrupt stopping of the boom near the position of the log leads to an oscillation of the grapple, which has to be compensated by a countermovement or by waiting before loading the log.

Based on the operator´s comments, machine operators during practical operations tend to load at a loading angle of 60–120° to the machine axis, thus, a loading angle of 135° seems to be less realistic. On rare occasions, at a 45° loading angle, the machine operator touched the stakes with the crane when the boom was extended. This observation might explain why a loading angle of at least 60° seems to be something of a lower limit in real operations. With the chosen setup, time consumption of only the three fixed loading angles could be assessed. However, the recorded data suggests that for intermediate stages between the selected loading angles, consistent intermediate time consumptions can be expected.

4.3. Influence of Log Orientation Angle on Time Consumption

Data analysis indicated that time consumption per loading cycle increased with higher log orientation angle.

This could be caused by an extended use of the rotator. The machine operator usually rotated the logs counter-clockwise into the load space. The additional function performed over the entire crane path was perceived by the operator as an additional cognitive strain and could be a reason for the higher time consumption. The movement seemed to be unfamiliar to the machine operator, since according to his statement, in many cases the logs are laid down at an angle of approximately 90° to the machine operating trail, and thus also to the machine axis. The effect of a parallel log orientation to the machine operating trail could not be observed with this study's setup. However, reduced time consumption owing to parallel log orientation is conceivable, as the rotator function needs to be actuated less. It has been shown that the coordination of several crane functions causes high mental workload for the operator [40].

4.4. Influence of Loading Distance on Time Consumption

The results have shown that in general there is no linear relationship between an increasing loading distance and time consumption per loading cycle.

The higher time consumption and variation in the closer range could be explained by the fact that the machine operator has to make full use of the motion range of the crane boom and stick, as well as the telescopic extension to pick up the log at this proximity. Furthermore, the test operator had to be careful not to damage the machine in some gripping positions, which could also be seen as a reason for the higher time consumption in the close-up area. In addition, the middle and ends of the logs in the close-up range at 135° (3 and 4 m) were partially not visible to the machine operator. This visibility of both ends of the log seemed to be highly important. In practice, problems could arise if only one end of the log is visible, as this might make it impossible to distinguish e.g., pulpwood from sawlogs, or other assortments. With the present study setup, it was not possible to load below 3 m distance to the crane pillar due to the length of the log.

Loading distances in the range of 7 m also required using the tested crane to its full motion range. All crane elements had to be brought into a horizontal orientation, the telescope was almost fully extended at a maximum crane reach of 7.5 m. This means that the machine operator had to be very sensitive when controlling the crane. When extending the telescope without cylinder end position damping, the crane began to jerk, which either needed to be compensated by counter-movements or by waiting until the log can be loaded.

Based on the results from this study, the loading range of 4–6 m could be described as the optimal loading range. It is important to emphasize that probably this is specific for the machine used and might also depend on the operator [13]. The distance between the crane pillar and the logs changes depending on the positioning of the forwarder. It can be assumed that positioning the machine at a distance between the logs and the crane pillar that matches the machine's crane geometry, results in lower time consumption per loading cycle. Basically, results from other studies indicate that machine positioning is one of the most important aspects of forwarder work when attempting to reduce time consumption caused by long loading distances [36,41]. Additionally, operators who spend a smaller share of total time driving due to better skills in positioning the machine, attain better productivity [42].

All in all, time consumption was significantly higher especially in the close range and at far loading distances (7 m) compared to loading distances of 4–6 m. In combination with loading angle, differences in time consumption between loading distances were illustrated most clearly by the comparison between the loading angles of 45° and 90°, versus 135°. In practice, loading at close range can probably often be ruled out. However, due to difficult stand or terrain conditions or poor preparatory work by the harvester operator, it could happen that logs are positioned at a closer distance to the machine. If the harvester positions the logs at the edge of the machine operating trail, it can be assumed that the distance to the crane pillar is sufficient to ensure a smooth work flow [37].

Despite the number of previous studies on factors affecting forwarder productivity [43] and since other regions of the world have an even higher level of mechanization in timber harvesting [44], it is worth taking a deeper look at further relevant aspects determining the performance of modern CTL systems. The effects of terrain or technical factors on the loading element itself should also be explored further, as studies revealed that especially the interaction between several productivity determining factors is crucial [45]. Other studies have shown that also diverse and more complex forest ecosystems strongly affect productivity, as these affect the mental workload on the operators [46], which could be examined for the forwarder as well. Through automation of work processes interlinked with digitalization [47,48], further research should aim to explore the suitability of technical devices such as rotating cabins or automated crane control to reduce the loading cycle time or the ergonomic strain on the operator. Results from other studies showed that, for example, boom tip control can improve crane work and loading productivity [49,50], in particular since the telescope no longer needs to be operated separately anymore [51–53].

5. Conclusions

The results indicate that all variables tested, i.e., loading angle, loading distance, and log orientation angle, significantly influenced time consumption of a standardized forwarder loading cycle. The in-depth consideration of the loading element, based on the results and discussion, allows three key conclusions for this case study:

- The time consumption per loading cycle increases with a higher loading angle;
- An increasing log orientation angle leads to increasing cycle times while loading;
- The loading distance affects time consumption per loading cycle, interacting with loading angle and log orientation angle.

In detail, loading logs from both a close and far position from the machine (distance of 3 m and 7 m) was less productive compared to medium loading distances (4–6 m). With an increase in loading angle (135°), this effect became more pronounced. Log orientation angle also showed a significant influence on time consumption per loading cycle. Based on the results of this study, forwarder loading in a 45° to 90° angle with a log orientation of approximately 90° relative to the machine operating trail requires the lowest time consumption per loading cycle.

Overall, the results of this case study give insight in the importance of three out of a great variety of factors which can potentially affect time consumption per loading cycle in forest operations. The results do not include interactions between the tested variables and other productivity determining factors in real operations. However, for improving efficiency of log extraction by forwarders, the results can show the impact of log positioning and orientation by harvester and machine positioning of the forwarder on the overall loading element. This may contribute to improving in-field operations resulting in more productive CTL harvesting operations.

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