Influence of Forest Machine Operator Work Practices and Operator Assistance Systems on the Efficiency of Fully Mechanized Timber Harvesting Systems

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Submitted by

Florian Hartsch

born on the 9th of June, 1993 in Hildesheim, Germany

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Members of the thesis committee:

1st Referee: **Prof. Dr. Dirk Jaeger**

Department of Forest Work Science and Engineering

Faculty of Forest Sciences and Forest Ecology

University of Göttingen

2nd Referee: **Prof. Dr. Carola Paul**

Department of Forest Economics and Sustainable Land-use Planning

Faculty of Forest Sciences and Forest Ecology

University of Göttingen

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This thesis is dedicated to Friedrich and Klara Marie.

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Summary

Introduction: Fully mechanized harvesting systems consisting of harvesters and forwarders represent state-of-the-art technology within modern timber harvesting operations. The droughts of the past years, consecutive bark beetle infestations and associated large-scale dieback of forests, especially of pure Norway spruce (*Picea abies*) stands, have once again shown that fully mechanized timber harvesting is well suited in the forestry sector due to high productivity and high occupational safety. Harvesters fell trees, process them according to bucking instructions and place the logs along machine operating trails. Forwarders load the logs, separated by assortment, and transport them to the landing.

Due to the complexity and heterogeneity of forest areas, various factors affect the productivity of these harvesting systems. In particular, stand and assortment parameters, terrain-related aspects, machine performance and -payload, and organizational aspects determine productivity, as well as environmental impacts, and the quality of timber harvesting. Research of recent years has shown that the forest machine operator in particular has considerable influence on these parameters. Experience and cognitive ability play an important role in terms of the "performance" of large machines. Forest machine operators work under high cognitive strain. Furthermore, work practices play a significant role in the economic performance as well as the ecological impact and the acceptance of fully mechanized timber harvesting within the population. Work practices characterize the individual execution of work methods, e.g., different crane operation mannerisms. These work practices can also have a negative impact on timber harvesting operations. To support the machine operator at work, guarantee productivity, and to ensure high work quality, assistance systems such as boom-tip controls and rotating cabins have become commonplace on the market in recent years.

The analysis of the interactions between work practices and operator assistance represents the core part of the present work. Work practices seem to have a decisive influence on the economic and ecological performance within timber harvesting. These work practices remain largely undefined and unknown in terms of their characteristics and effects in the context of forest machine operations. The performance of the forwarder operator is especially critical to the overall productivity of fully mechanized timber harvesting systems. Taking a deeper look at forwarding activities, the loading element occupies nearly 50% of the total forwarding cycle time. However, it is unclear how forwarder operator work practices affect the time required per loading cycle. For example, depending on the precursory work of the harvester operator and the positioning of the forwarder thereafter, different loading distances, loading angles, and log orientation angles result. Furthermore, it remains unclear to what extent machine operator assistance can reduce the forwarder's loading cycle time. Therefore, the present work pursued the following objectives: Firstly, to define and quantify positive and negative work practices in the context of fully mechanized timber harvesting. Secondly, to quantify the effects

of different loading distances, loading angles, and log orientation angles, partly resulting from the harvester's precursory work, on the forwarder's loading cycle time consumption. Thirdly, to investigate the effects of the use of forest machine operator assistance systems on the time consumption per loading cycle of forwarders.

Methods Paper I: To achieve the research objectives, a multi-stage approach was chosen comprising three different studies reported in individual publications. Since work practices and their effects are largely unknown in the context of fully mechanized timber harvesting, a combination of literature analysis and expert interviews was performed within **Paper I**. The literature search followed the PRISMA approach and ultimately integrated 16 references into the analysis where evidence of positive and negative work practices was found. A semi-structured interview guide was developed as part of the expert interviews. After conducting the interviews with 15 forest machine operator instructors from Germany, Sweden and Norway, audio files were transcribed, anonymized, and analyzed using MAXQDA software. A coding system was used to assign statements relevant to the research objective.

Results Paper I: The results of **Paper I** revealed that the work practices of forest machine operators might have a decisive influence on productivity as well as machine wear and fuel emissions within fully mechanized timber harvesting systems. The literature review showed that scientific literature only sparsely covers the analysis of forest machine operator work practices. The interviews, on the other hand, resulted in an extensive list of work practices within crane work, machine positioning, work organization, value creation, and teamwork. Therefore, work practices can be described as positive if they lead to increased productivity of both harvesters and forwarders, decreased fuel consumption and thus carbon footprint, optimized value creation through optimized harvesting, or simply improved cooperation between harvester and forwarder operators. Based on the results, "positive" work practices can be quantified as follows (excerpt): Positioning the machine within ("productive") crane reach of as many trees to be felled (harvester) or logs to be loaded (forwarder) as possible, frequent repositioning of the machine, regular maintenance of the machine, crane speed adjustments related to personal preferences, separate positioning of logs by assortment after processing (harvester) or frequent use of the telescope during the entire crane operations. If a machine operator does not follow these and other aspects (Paper I), the work practices methods can be considered as "negative".

Methods Paper II: In **Paper II**, an experiment with standardized loading cycles was conducted to investigate the effects of loading distance, loading angle, and log orientation angle on time consumption of forwarder loading cycles. A professional forest machine operator was tasked with performing loading cycles on a realistic forwarder simulator at the Forest Education Center in Münchehof. To achieve a range of loading scenarios, five different loading distances (3 m, 4 m, 5 m, 6 m, 7 m) and three different loading angles (45°, 90° and 135° azimuthal to the machine axis) were tested. For each of these 15 loading positions, the log orientation angle was also varied (45°, 90° and 135° to the machine axis). These 45 test setups, with 10 repetitions each, resulted in a total of 450 loading cycles, recorded by stopwatch and video.

Results Paper II: The results of the first field study, published in **Paper II**, showed that work practices of forest machine operators can have a significant impact on the time consumption per loading cycle of a forwarder. All tested variables (loading distance, loading angle, and log orientation angle) had a significant impact on the time required per loading cycle. Based on the results, optimal loading ranges could be identified. On the opposite, the highest time requirement for loading was observed for the distance range closest to the machine (3 m) and for the range furthest from the machine (7 m), where no significant difference between the two distance ranges could be observed. However, in medium loading distances (4-6 m), significant differences in loading time from the 3 m and 7 m loading distances were observed. The loading cycle time also increased with increasing loading angles. The lowest time requirement was observed for the 45° and 90° angles, respectively. The loading cycle duration also increased with increasing log orientation angle. Compared to the reference replicate, significant increases in loading cycle time of up to 75% were observed when the machine operator loaded logs from close to the machine (3 m), at a 135° loading angle and a log orientation angle of 90°.

Methods Paper III: In **Paper III**, the methodology of **Paper II** was adapted and supplemented. The machine type and the machine operator were changed, the loading angles (55°, 90° and 125° to the machine axis) and loading distances (4 m, 5.5 m, 7 m, 8.5 m, 10 m) were adapted. Since the effect of machine operator assistance (boom-tip control, "IBC" and John Deere rotating cab) on time consumption per loading cycle was studied, the 15 loading positions were tested, but with four variants: 1. IBC and rotating cabin deactivated; 2. IBC deactivated and rotating cabin activated; 3. IBC activated and rotating cabin deactivated; 4. IBC and rotating cabin activated. A total of 60 sub-variants were tested in 10 repetitions each, which resulted in a total of 600 loading cycles.

Results Paper III: The results of **Paper III** revealed that rotating cabins alone did not significantly reduce time consumption per loading cycle for a forwarder. Boom-tip controls, on the other hand, significantly reduced loading cycle time. When crane tip controls and rotating cabs were both activated, time consumption per loading cycle was significantly reduced by up to 14%. The effects of these assistance systems were mainly evident within medium loading distance (5.5-8.5 m) setups, while the effect was smaller at closer (4 m) and further loading distances (10 m). The shortest time consumption per loading cycle was achieved at 4 m loading distance, at a 55° loading angle, using boom-tip control and rotating cabin assistance. Compared to this variant, the time consumption per loading cycle increased significantly, by up to 66%, when working at a loading distance of 10 m, at a 55° loading angle, with boom-tip control and rotating cabin deactivated.

General discussion: The results of **Paper I** showed that work practices of forest machine operators and also their productivity (measured via time consumption per loading cycle within the present studies) were closely linked. Due to the limited sample size, the insights provided into work practices of forest machine operators cannot represent the working behavior of the full population of forest machine operators in Germany and Scandinavia. However, expert interviews offered reasonable insight into the work practices of machine operators working in Germany and Scandinavia. Due to the competence of the interviewees to communicate interview responses proficiently, many years of experience and the high number of trained and educated operators, it can be assumed that the identified work practices also play a significant role in practice. Above all, the literature analysis showed that work practices in forest science have only been sparsely characterized. An investigation into work practices and their effects on different aspects within the cooperation between harvester and forwarder operator is strongly recommended. Related to this aspect, the results of **Paper II** showed a statistically significant effect of loading distance, loading angle, and log orientation angle on the forwarder´s time consumption per loading cycle. Preliminary studies and observations of other machine operators suggest that the observed patterns could hold true for the performance of other operators as well. Therefore, conclusions can be drawn from the results that can be used in the context of defining "best practices" within fully mechanized timber harvesting systems. Based on the results and therefore to optimize forwarder loading, a harvester operator should deposit the logs as close to the machine operating trail as possible (to reach optimal loading distances for the forwarder), at a 45° or 90° angle, and the forwarder operator should position his machine so that the loading distance is as short as possible, and the loading angle does not exceed 90°. The results can therefore also be used in forest machine operator education. In **Paper III**, it was observed that synergies occur when rotating cabins and boom-tip control are used simultaneously. This combination can significantly reduce the time consumption per loading cycle of a forwarder by up to 14%. Based on experience reports and observations, as well as the results of other scientific studies, it can be assumed that the results presented are in-line with practice. This shows that the use of operator assistance can have positive effects on the loading cycle duration, and thus also on productivity in fully mechanized timber harvesting. The effects of operator assistance on mental and physical strain could not be investigated. However, it seems likely that the use of boom-tip controls in particular, could reduce mental strain by eliminating the need to operate the telescope. Based on observations, a rotating cabin could lead to a reduced number of movements that are considered harmful to the upper body.

Overall, it can be stated that in Central European forestry change is underway due to catastrophic events affecting the timber stock and technical innovations in the timber harvesting sphere. For reasons of productivity and occupational safety, fully mechanized timber harvesting systems have been commonplace in the timber harvesting sector for several decades now. Large-scale technical revolutions should not be expected in the coming years, which is why fully mechanized harvesting systems, which represent a significant part of the entire wood production process, will most likely to be rationalized through integrative data utilization and the use of operator assistance systems. In times of tense labor markets, it is even more important to attract and retain well-qualified and motivated specialists in forestry, including forest operations. This is not possible through attractive remuneration alone - a modern workplace that relieves the machine operator and increases job satisfaction should be part of the solution to the problem as well.

Zusammenfassung

Einleitung: Hochmechanisierte Holzerntesysteme bestehend aus Harvester und Forwarder entsprechen dem Stand der Technik innerhalb der modernen Holzernte. Die Dürren der vergangenen Jahre, konsekutiver Borkenkäferbefall und damit in Verbindung stehendes großflächiges Absterben von Wäldern, insbesondere Fichtenreinbeständen (*Picea abies*), hat einmal mehr gezeigt, dass die vollmechanisierte Holzernte aufgrund der hohen Produktivität und der hohen Arbeitssicherheit am Markt unerlässlich ist. Harvester fällen Bäume, arbeiten diese entsprechend der Sortimentierung auf und legen die Abschnitte am Rand der Rückegasse ab. Forwarder laden die Abschnitte möglichst sortenrein und bringen diese dann zum Polterplatz.

Aufgrund der Vielschichtigkeit und Heterogenität von Forstflächen üben diverse Faktoren einen Einfluss auf die Produktivität dieser Holzerntesysteme aus. Insbesondere Bestandes- und Rundholzparameter, das Gelände, die Leistung und Zuladung der Forstmaschinen und organisationale Aspekte bestimmen Produktivität, Emissionen, sowie den Grad an Pfleglichkeit der Holzernte. Forstwissenschaftliche Untersuchungen der vergangenen Jahre zeigten, dass insbesondere auch der Forstmaschinenführer einen erheblichen Einfluss auf diese Parameter ausübt. Erfahrung spielt ebenso wie die kognitiven Fähigkeiten eine Rolle hinsichtlich der "Performance", die auf Großmaschinen gezeigt werden kann. Die mentale Beanspruchung ist bei Forstmaschinen als hoch einzustufen. Des Weiteren spielen Arbeitsweisen bei der ökonomischen Leistungsfähigkeit sowie der ökologischen und sozialen Verträglichkeit der Holzernte eine bedeutende Rolle. Arbeitsweisen kennzeichnen die individuell-subjektive Ausführung von Arbeitsmethoden, beispielsweise je nach Forstmaschinenführer unterschiedliche Ausprägungen der Kranbedienung. Diese Arbeitsweisen können sich im Zweifel auch negativ auf das Arbeitsergebnis bei Holzerntemaßnahmen auswirken. Um den Maschinenführer bei der Arbeit zu unterstützen, und um die Produktivität sowie ein noch bestandesschonenderes Arbeiten zu erreichen, haben sich am Markt in den vergangenen Jahren Assistenzsysteme wie Kranspitzensteuerungen und drehbare Kabinen etabliert.

Gerade diese Analyse der Wechselwirkungen zwischen Arbeitsweisen und Maschinenführerassistenz stellte den Kern der vorliegenden Arbeit dar. Arbeitsweisen scheinen die ökonomischen, ökologischen und sozialen Auswirkungen der hochmechanisierten Holzernte entscheidend zu beeinflussen, verbleiben aber weitestgehend undefiniert und unbekannt in ihren Ausprägungen und Auswirkungen im Rahmen der Bedienung von Forstmaschinen. Insbesondere die Leistung des Forwarderfahrers ist ebenfalls entscheidend für die Gesamtproduktivität hochmechanisierter Holzerntesysteme. Das Laden macht rund die Hälfte der Gesamtzykluszeit beim Forwarder aus. Auch hier ist jedoch unklar, wie sich Arbeitsweisen von Forwarderfahrern auf den Zeitbedarf pro Ladezyklus auswirken. So resultieren je nach Vorarbeit des Harvesterfahrers und der Positionierung des Tragschleppers beispielsweise

unterschiedliche Ladedistanzen, Ladewinkel und Ablagewinkel von Rundholzabschnitten. Weiterhin bleibt unklar, inwieweit Maschinenführerassistenz in der Lage ist, die Ladezyklusdauer beim Forwarder zu senken. Daher verfolgte die vorliegende Arbeit folgende Ziele: Erstens sollte eine Definition und Einordnung von positiven und negativen Arbeitsweisen im Rahmen der hochmechanisierten Holzernte vorgenommen werden. Zweitens sollten in einer Feldstudie die Auswirkungen verschiedener Ladedistanzen, Ladewinkel und Ablagewinkel von Rundholzabschnitten, teilweise resultierend aus der Vorarbeit des Harvesters, auf die Ladezyklusdauer untersucht werden. Drittens war es erklärtes Ziel der vorliegenden Arbeit, im Rahmen einer weiteren Studie die Auswirkungen der Nutzung von Maschinenführerassistenz auf die Ladezyklusdauer von Forwardern zu untersuchen.

Material und Methoden Publikation I: Zur Erreichung der Forschungsziele wurde je nach Publikation ein mehrstufiger Ansatz gewählt. Da Arbeitsweisen und deren Auswirkungen im Rahmen der hochmechanisierten Holzernte weitestgehend unbekannt sind, wurde im Rahmen von **Paper I** eine Kombination aus Literaturanalyse und Experteninterviews angewandt. Die Literatursuche folgte dem PRISMA-Ansatz und integrierte letztendlich 16 Referenzen in die Analyse, in denen Hinweise auf positive und negative Arbeitsweisen zu finden waren. Im Rahmen der Expertenbefragungen wurde ein teilstrukturierter Interviewleitfaden entwickelt. Nach den Interviews mit 15 Forstmaschinenführerausbildern aus Deutschland, Schweden und Norwegen wurden die Audiodateien transkribiert, anonymisiert und mit der Software MAXQDA ausgewertet. Die Zuordnung der für das Forschungsziel relevanten Aussagen erfolgte mittels eines Kodiersystems.

Ergebnisse Publikation I: Die Ergebnisse von **Paper I** zeigten, dass Arbeitsweisen von Forstmaschinenführern sowohl die Produktivität, als auch den Maschinenverschleiß oder auch Kraftstoffemissionen hochmechanisierter Holzerntesysteme entscheidend beeinflussen. Die Literaturanalyse zeigte, dass wissenschaftliche Literatur bis dato Arbeitsweisen nur unzureichend berücksichtigt. Die Befragungen hingegen brachten eine umfangreiche Liste von Arbeitsweisen in Kranarbeit, Positionierung der Maschinen, Arbeitsorganisation, Wertschöpfung und Teamarbeit hervor. Arbeitsweisen können dann als positiv bezeichnet werden, wenn die Produktivität einzelner Systemkompartimente steigt, der Kraftstoffverbrauch und damit Kohlenstoffdioxidemissionen sinken, die Wertschöpfung durch optimierte Aushaltung optimiert oder die Zusammenarbeit zwischen Harvester- und Forwarderfahrer verbessert wird. Auf Basis der Ergebnisse können „positive“ Arbeitsweisen folgendermaßen quantifiziert werden (Auszug): Die Positionierung der Maschine in Reichweite möglichst vieler zu fällender Bäume (Harvester) oder zu ladender Abschnitte (Forwarder), die regelmäßige Umpositionierung des Kranvollernters bzw. Tragschleppers, eine regelmäßige Durchführung der Maschinenwartung, das Anpassen der Krangeschwindigkeit auf die persönlichen Präferenzen des Maschinenführers, oder das sortimentsweise Ablegen der Abschnitte nach der

Aufarbeitung (Harvester) bzw. der Einsatz des Teleskops bei der gesamten Kranarbeit. Wenn ein Maschinenführer diese und weitere Aspekte nicht beachtet (Publikation I), sind die Arbeitsweisen als „negativ" zu kennzeichnen.

Material und Methoden Publikation II: Im Rahmen von **Paper II** wurden zur Untersuchung der Auswirkungen von Ladeentfernung, Ladewinkel und Ablagewinkel von Rundholzabschnitten auf die Ladezyklusdauer beim Forwarder standardisierte Ladezyklen abgebildet. Ein professioneller Forstmaschinenführer hatte die Aufgabe, auf einem realitätsnahen Forwardersimulator am Forstlichen Bildungszentrum in Münchehof Ladezyklen durchzuführen. Um die Szenarien zu variieren, wurden fünf verschiedene Ladeentfernungen (3 m, 4 m, 5 m, 6 m, 7 m) in drei Ladewinkeln (45°, 90° und 135° azimutal zur Maschinenachse) getestet. Innerhalb dieser 15 Ladepositionen wurden die Ablagewinkel der Rundholzabschnitte variiert (45°, 90° und 135° zur Maschinenachse). 45 Versuchssettings, versehen mit jeweils 10 Wiederholungen, resultierten in insgesamt 450 Ladezyklen, die mit Stoppuhr und Video aufgenommen wurden.

Ergebnisse Publikation II: Die Ergebnisse der ersten Feldstudie, veröffentlicht in **Paper II** zeigten, dass Arbeitsweisen von Forstmaschinenführern einen erheblichen Einfluss auf den Zeitbedarf pro Ladezyklus ausüben können. Alle getesteten Variablen (Ladeentfernung, Ladewinkel und Ablagewinkel von Rundholzabschnitten) hatten einen signifikanten Einfluss auf die Ladezyklusdauer. Auf Basis der Ergebnisse konnten optimale Ladezonen identifiziert werden. Der höchste Zeitbedarf zum Laden wurde im Nahbereich an der Maschine (3 m) sowie in weiteren Entfernungen beobachtet (7 m), innerhalb dieser beiden Varianten konnte kein signifikanter Unterschied herausgearbeitet werden. In mittleren Ladeentfernungen (4-6 m) bestanden hingegen signifikante Unterschiede zur 3- und 7 m-Ladeentfernung. Die Ladezyklusdauer stieg ebenfalls mit steigendem Ladewinkel. Der geringste Zeitbedarf war hier bei 45° respektive 90° zu beobachten. Auch mit steigendem Ablagewinkel stieg die Ladezyklusdauer. Im Vergleich zur Referenzvariante waren signifikante Steigerungen des Zeitbedarfs um bis zu 75% zu beobachten, sofern der Maschinenführer nah an der Maschine (3 m), im 135° Winkel arbeitete, und unter Berücksichtigung eines Rundholzablagewinkels von 90° Abschnitte in den Rungenkorb legte.

Material und Methoden Publikation III: Im Rahmen von **Paper III** wurde dieses Design adaptiert und ergänzt. Der Maschinentyp sowie der Maschinenführer wurden gewechselt, die Ladewinkel (55°, 90° und 125° zur Maschinenachse) und -entfernungen (4 m, 5.5 m, 7 m, 8.5 m, 10 m) angepasst. Da Maschinenführerassistenz (Kranspitzensteuerung, "IBC" und drehbare Kabine von John Deere) in ihrer Auswirkung auf die Ladezyklusdauer untersucht wurde, wurden die 15 Ladepositionen mit vier Varianten versehen: 1. IBC und drehbare Kabine deaktiviert; 2. IBC deaktiviert und drehbare Kabine aktiviert; 3. IBC aktiviert und drehbare Kabine deaktiviert; 4. IBC und drehbare Kabine aktiviert.

Insgesamt 60 Teilvarianten wurden mit einer Wiederholungszahl von 10 versehen und resultierten in der Aufnahme von 600 Ladezyklen insgesamt, mit Stoppuhr und Video.

Ergebnisse Publikation III: Die Ergebnisse in **Paper III** zeigten, dass drehbare Kabinen allein keinen signifikanten Einfluss auf die Ladezyklusdauer beim Forwarder ausübten. Kranspitzensteuerungen hingegen hatten einen signifikanten Einfluss auf die Ladezyklusdauer. Sofern Kranspitzensteuerungen und drehbare Kabinen hingegen gemeinsam eingesetzt wurden, reduzierte sich die Ladezyklusdauer signifikant um bis zu 14% pro Ladezyklus. Die Auswirkungen der Assistenzsysteme zeigten sich hauptsächlich in mittleren Ladeentfernungen (5.5-8.5 m), im Nahbereich an der Maschine (4 m) und in weiten Ladeentfernungen (10 m) war der Effekt geringer. Die kürzeste Ladezyklusdauer wurde in 4 m Ladeentfernung erreicht, in einem Ladewinkel von 55°, unter Einsatz von Kranspitzensteuerung und drehbarer Kabine. Im Vergleich zu dieser Variante erhöhte sich die Ladezyklusdauer signifikant um 66%, wenn in 10 m Entfernung im 55°-Winkel unter Ausschluss von Kranspitzensteuerung und drehbarer Kabine gearbeitet wurde.

Allgemeine Diskussion: Die Ergebnisse von **Paper I** zeigten, dass Arbeitsweisen und Produktivität, in den vorliegenden Studien gemessen an der Ladezyklusdauer, eng miteinander verflochten sind. Die gewährten Einblicke in Arbeitsweisen von Forstmaschinenführern können aufgrund der begrenzten Stichprobenanzahl nicht die volle Grundgesamtheit der Forstmaschinenführer in Deutschland und Skandinavien repräsentieren. Da aber keine qualifizierte Schätzung der in Deutschland und Skandinavien tätigen Maschinenführer möglich ist, wurde sich zur Durchführung explorativer Expertenbefragungen entschieden. Aufgrund des hohen Levels an Professionalität der Befragten sowie der (oft) langjährigen Erfahrung und einer hohen Anzahl an aus- und fortgebildeten Personen ist aber davon auszugehen, dass die identifizierten Arbeitsweisen auch in der Praxis eine bedeutende Rolle spielen. Die Literaturanalyse zeigte vor allem, dass Definitionen von Arbeitsweisen in der forstwissenschaftlichen Forschung bis dato eher als Nebenergebnisse von Untersuchungen auftraten. Eine Untersuchung von Arbeitsweisen als solchen mit ihren Auswirkungen auf verschiedene Aspekte in der Zusammenarbeit zwischen Harvester und Forwarder wird ausdrücklich empfohlen. In diesem Zusammenhang zeigten die Ergebnisse aus **Paper II** einen statistisch signifikanten Einfluss von Ladeentfernung, Ladewinkel und Ablagewinkel von Rundholzabschnitten auf die Ladezyklusdauer beim Forwarder. Die Ergebnisse sind aufgrund des geringen Stichprobenumfanges zwar differenziert zu betrachten. Vorstudien und Beobachtungen von anderen Maschinenführern legen jedoch nahe, dass die beobachteten Muster auch dort auftreten können. Aus den Ergebnissen lassen sich daher Schlüsse ziehen, die im Rahmen der Definition von "best practices" bei der Arbeit von hochmechanisierten Holzerntesystemen genutzt werden können. Ein Harvesterfahrer sollte die Rundholzabschnitte möglichst nah und rechtwinklig an der Gasse ablegen, der Forwarderfahrer sollte sich dergestalt positionieren, dass die Ladeentfernung möglichst kurz, der Ladewinkel nicht über 90° liegen sollte. Die Ergebnisse können so auch in der Forstmaschinenführerausbildung eingesetzt werden. In **Paper III** wurde gezeigt, dass insbesondere beim Einsatz von drehbaren Kabinen und Kranspitzensteuerung gemeinsam Synergien entstehen, die die Ladezyklusdauer eines Forwarders um bis zu 14% signifikant reduzieren können. Aufgrund des geringen Stichprobenumfanges sind auch hier die Ergebnisse differenziert zu betrachten. Auf Basis von Erfahrungsberichten und Beobachtungen sowie den Ergebnissen anderer wissenschaftlicher Studien ist jedoch davon auszugehen, dass sich die vorgestellten Ergebnisse mit der Praxis decken. Dies zeigt, dass der Einsatz von Fahrerassistenz positive Auswirkungen auf die Ladezyklusdauer, und damit auch die Produktivität in der Holzernte, haben kann. Nicht untersucht wurden Effekte von Fahrerassistenz auf die mentale und körperliche Beanspruchung. Es liegt jedoch nahe, dass insbesondere der Einsatz von Kranspitzensteuerungen die mentale Beanspruchung reduzieren könnte, da die Teleskopfunktion nicht mehr bedient werden muss. Eine drehbare Kabine kann auf Basis von Beobachtungen zu einer deutlich reduzierten Anzahl von für den Oberkörper schädlichen Bewegungen führen.

Insgesamt ist festzustellen, dass sich die mitteleuropäische Forstwirtschaft aufgrund von Kalamitäten und technischen Neuerungen im Umbruch befindet. Hochmechanisierte Holzerntesysteme haben sich aus Gründen der Produktivität und Arbeitssicherheit seit mehreren Jahrzehnten am Markt etabliert. Technische Revolutionen sind in den kommenden Jahren eher nicht zu erwarten, weshalb hochmechanisierte Holzerntesysteme, die einen bedeutenden Teil des gesamten Holzproduktionsprozesses darstellen, am ehesten über integrative Datennutzung sowie den Einsatz von Assistenzsystemen zu rationalisieren sind. In Zeiten akuten Fachkräftemangels gilt es in der Forstwirtschaft, auch auf Forstmaschinen, umso mehr, gut qualifizierte und motivierte Fachkräfte zu gewinnen und zu halten. Dies ist nicht ausschließlich über das Gehalt möglich – ein moderner Arbeitsplatz, der den Maschinenführer entlastet und die Arbeitszufriedenheit erhöht, sollte genauso Teil der Problemlösung sein.

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1. Introduction

1.1 Theoretical background

1.1.1 Current state of forestry and timber harvesting in Europe

Forestry and forest management are currently changing all over Europe. Central European forests are facing major economic, ecological and social challenges. A lack of precipitation, large scale species extinction, and needs of the urban population to participate in forestry, have led to increased demand on modern forest management and forest operations, especially (BMEL 2021). Furthermore, forestry is facing global megatrends, which are currently manifesting themselves and challenging the ways companies have operated in recent decades. In particular, climate change and digitalization and demographic-related changes in the forestry sector and in the labor market are leading to profound challenges (Helmrich et al. 2020). Economic, ecological, and social adaptability will have an even greater significance in the forestry sector in the near future (Umweltbundesamt 2023). To meet these challenges, the federal government of Germany revised the national forest strategy years ago already. In a nutshell, forests in central Europe shall become more structurally diverse in conjunction with the establishment of additional resilient tree species. The goal of this strategy is to increase climate stability of the forests (BMU 2020) and therefore to reduce the economic risk of forest failure. Great forest areas, especially old broadleaved forests within public property, have already been taken out of management or will be fully protected within the next years (Bolte et al. 2022). These and more strategy-related aspects intend to deeply affect productivity of fully mechanized harvesting systems in the near future.

However, forestry and fully mechanized timber harvesting still enjoy a great importance in Europe, as forest management is related to economic aspects (§ 1 BWaldG). In general, forests in Germany cover about 32% of the total land surface area, which means that a total of 11,4 mio. ha (BMEL 2014) of forests need to be managed, with only a few exceptions (e.g. National Parks). The German forestry and wood processing sector consisting of its associated administrations and companies happens to be one of the most important employers. A total of more than one million employees, generating a total turnover of more than €187 billion (BMEL 2023), is directly or indirectly associated with forests. In Germany, nearly 80 mio. m³ of timber was harvested in 2022 (Destatis 2023). The catastrophic events (storms, droughts and related bark beetle infestations) of the last few years have caused wood damages totaling approximately 44,7 million m³ or 57% of the total annual harvesting volume within 2022 (Destatis 2023). In 2022, the share of Norway spruce and (Douglas) fir related to the total harvested volume amounted to approximately 60% (Destatis 2023). Today, more than 50% of timber harvested is done so by means of fully mechanized systems (LWK NRW 2023). In 2003, this percentage was approximately 20 – 30% (Hamberger 2003), which means that the importance of these systems has increased.

1.1.2 Fully mechanized harvesting systems within timber production

The overall timber production process as part of the wood supply chain is multi-layered and can be divided into a total of three production levels (Thees 2015, cited by DFWSE 2023 a):

- Biological production: Describes the silvicultural management, the establishment and cultivation of stands.
- Technical production: Describes the timber production process, from the tree in the forest stand to the raw timber.
- Processing: Describes the process from the raw timber in the mill, to the final wood product.

These production levels would be followed by the utilization of the products by the consumer as well as disposal, provided that the entire value chain is considered (Thees 2015, cited by DFWSE 2023 a). Fully mechanized timber harvesting systems within "Cut-to-length" processes are part of the technical production and consist of harvesters and forwarders. These are state-of-the-art technology for felling, processing, and extracting timber. In standardized cut-to-length systems, harvesters fell the livingor dead tree. The harvested tree is then placed in the direction of the machine operating trail. Ideally, the full tree is then processed (debranched and bucked into assortments) directly on the machine operating trail to produce brush mats to reduce soil disturbance. After completing processing and bucking cuts, the harvester operator deposits the logs at the edge of the machine operating trail. Forwarders also operate along these trails, whereby logs are extracted from the stand and transported to the landing. This work method is also designated as Cut-to-length (CTL) method (Ponsse 2023 a). Within forest work science, work elements within CTL work systems can be defined as follows: *Driving, Crane Use, Felling, Processing, Manipulation* (harvester) (Nuutinen 2013) and *Driving loaded, Driving empty, Loading, Unloading* (forwarder) (Ghaffarian et al. 2007). One of the most important requirements for the use of harvesters and forwarders without motormanual support is the distance between the machine operating trails, which should be approximately 20 m (LWF 2017). Due to conservation and soil protection, the distance between machine operating trails is increasing (Landesbetrieb Wald und Holz NRW 2013). The timber harvesting and forwarding process, called "Cut-to-length", is shown in **Figure 1**.

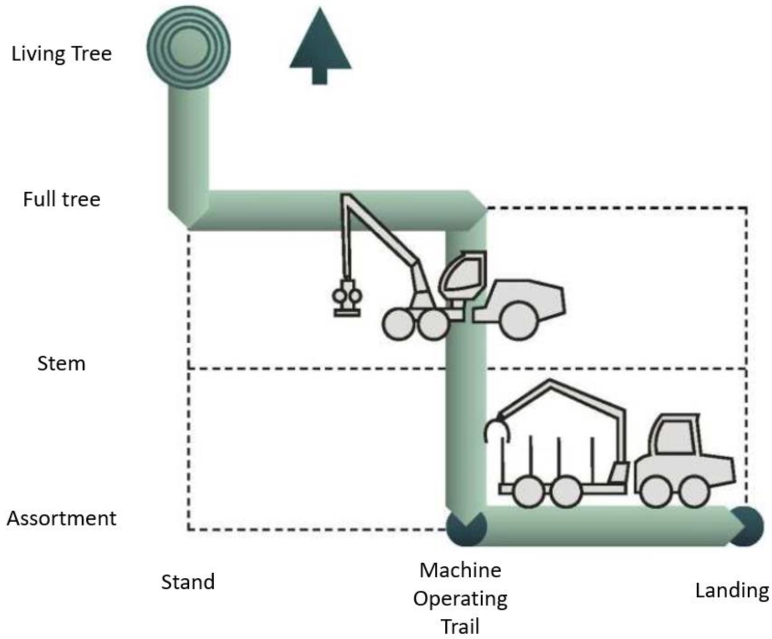

Figure 1: *Sequence of processing and transport within the typical Cut-to-length system (Erler and Dög 2009, cited by DFWSE 2023, translated).*

Fully mechanized harvesting systems have become established as a working system. In Scandinavia, harvesters have been commonplace since the 1980´s (Metsähallitus 2023). In Germany, the major storms “Vivian” (1990), “Wiebke” (1990), “Lothar” (1999), “Kyrill” (2007) and “Friederike” (2018) (Fichtelbergwetter 2023) affected forestry operations. Originally, two-grip harvesters were used, which worked with separate felling and processing units. Current single-grip harvesters are equipped with a harvester head, which is able to fell, delimb and cross-cut trees (Fleischer 2007). A special case within highly mechanized harvesting is the use of fellerbunchers. A fellerbuncher is able to fell stems and collect them in the aggregate, to subsequently deposit bundles of stems on the ground. These systems can also manage smaller diameter trees for energy and pulp production (Eberhardinger 2023). Working with harvesters and forwarders is popular for two reasons: Firstly, these systems are extremely productive. A harvester (operator) fells and processes around 10 to 25 m³ of wood per hour (Purfürst 2009), while a forwarder (operator) is capable of forwarding between 4 and up to 15.7 m³ of timber per machine hour (Valenta and Neruda 2004, Proto et al. 2018), based on the stem volume and other related aspects (see chapter 3.3). Total harvesting and forwarding costs range from between €14,50 and €26,50 per m³ of wood (ThüringenForst 2023). Secondly, harvesters and forwarders have become established due to a high degree of occupational safety they provide. Compared to semi-mechanized work systems with motor-manual support, harvester work is safer (KWF 2023).

Both harvesters and forwarders (i.e. system components) function within one working system and interact with each other. Communication between harvesters and forwarders can take place digitally, but practice often shows that operators and companies prefer analog paths. Harvesters are equipped with On-Board-Computers (OBC), which collect a large amount of data on the processed timber standardized according to StanForD-2010. These data include information on the harvested production, which is captured as .hpr files during operation (Skogforsk 2010). During and after the felling and processing operation, the forwarder operator can view digital or analog information about the total amount of harvested timber, or even the position of the piles to better plan the next operations (John Deere 2023 a).

As the communication between both system compartments is essential, insufficient contact between the operators can lead to economic and ecological losses. Poor communication and therefore, a lack in efficient planning of harvesting operations, can cause cross-cuts to be executed inappropriately, log sorting not carried out according to the assortment stipulations, or wood left behind in the stands (Persson 2013). Communication aside, clarity about productivity-related aspects is key to a successful harvesting operation.

The productivity of such fully mechanized harvesting systems is influenced by various factors. These can be classified as follows, according to Hartsch et al. (2022 a):

- Stand and timber characteristics,
- Terrain-related aspects,
- Machine-related parameters,
- Organizational aspects,
- Machine operator.

1.1.3 Forest machine operators and their importance in timber harvesting

As “business-oriented” forest owners evaluate harvesting operations from an economic, ecological, and social perspective, the performance of harvester and forwarder operators is frequently scrutinized (Persson 2013). The forest machine operator influences not only the whole system’s productivity (Purfürst 2010), but also the reputation of the contractor (Persson 2013). Operating forest machines is quite difficult and requires multi-tasking competencies as operators need to stay in contact with customers, avoid stand and soil damages, and behave “properly” (Persson 2013). The demand placed on forest management by forest visitors regarding environmental-friendly forest operations has increased over the past years (Schulz and Meyer 2021) and can lead to conflicts concerning suitable, environmentally conscious practices (Persson 2013). Therefore, operators have an immense responsibility to carry out their jobs according to the stipulated forest management principles. Team spirit is furthermore necessary to achieve the goals of a harvesting operation (Persson 2013).

Harvester and forwarder operators work under high cognitive load. Nearly three years of training are necessary to reach the full aptitude to operate forest machinery (Purfürst 2010). Operator training programs are lengthy and consist of extensive modules in business organization, fully mechanized harvesting operation, semi-mechanized timber processing and forwarding operations (LWK NRW 2023). Although productivity usually increases with experience, even professional forest machine operators can show productivity differences of up to 40% (Ovaskainen et al. 2004).

To reduce these productivity differences, while still achieving environmentally and socially conscious forest operations, two approaches are possible:

Firstly, it is well established practice in Germany and many other countries, to train and educate forest machine operators both before and during their career, to change working or improve working behavior (Ranta 2009). Studies show that forest machine operator training using simulators can increase productivity and decrease repair and maintenance costs (Lapointe and Robert 2000). Training on forest machine simulators is common practice in German forest education centers, which offer machine operator training courses, e.g.: Arnsberg (Northrhine-Westfalia), Münchehof (Lower Saxony) and Kunsterspring (Brandenburg) (LWK NRW 2023, LWK NDS 2023, LFBB 2023). Machine operator education in Germany is a state-certified professional qualification. However, courses are modular with various theoretical and practical components, which means that even professional operators can participate in single modules to improve their skills (LWK NRW 2023).

The second possibility to reduce productivity differences and through reducing mental strain is to use operator assistance systems.

1.1.4 Operator Assistance, boom-tip control and rotating cabins

Operator assistance can be defined in different ways. Machine manufacturers claim operator assistance to simplify machine operation and increase productivity, “retain(ing) the best operators” (John Deere 2023 b).

In the automotive industry, operator assistance can basically be divided into three classes (Prawitz 2022):

- Informing operator assistance
- Supporting operator assistance
- Intervening operator assistance

In accordance with the above-mentioned classification, operator assistance can also be divided into cognitive assistance (perception- and decision assistance) and physical assistance (executive assistance) (Galaske et al. 2019). Perception- and decision assistance related to forestry could be practically defined as sensor-related detection of the machine's surrounding in combination with a visualization of trees to be harvested, shown on the operator's heads-up displays (Horvath et al. 2022). However, not all of these systems and classifications seem to be highly relevant to forestry, as operating forest machines largely differs from road traffic. Therefore, two systems highly relevant for operational usage within fully mechanized harvesting systems were tested or analyzed within this, namely boom-tip control and rotating cabins.

Boom-tip control, such as "Intelligent Boom Control (IBC)" (John Deere 2023 c), includes sensors within the hydraulics, which allows the operator to focus on controlling only the boom-tip position while the boom/crane itself adjusts its movements accordingly (John Deere 2023 c). Manufacturers advertise increased productivity, faster learning processes, more job satisfaction, and decreased fuel consumption (John Deere 2023 b). Almost all market-established manufacturers, including John Deere, introduced boom-tip control, designated e.g. "Active crane" (Ponsse 2023 b) or "Smart Crane" (Komatsu 2023). Scientific studies reveal that these boom-tip controls can increase productivity and make crane control easier for the operators (Manner et al. 2017, Manner et al. 2019).

With rotating cabins, the cabin the operator resides in is able to follow the grapple's movement across 290° of motion, depending on the machine type. With an enhanced view of the working area, manufacturers advertise increased efficiency and optimized ergonomics. The self-levelling function can provide further support on sloped work areas (John Deere 2023 e). Studies from other scientific disciplines and clusters also reveal that operator assistance is able to increase productivity, reduce mental workload and optimize work flow (John Deere 2023 b). The workflow itself is strongly connected to work methods and operator work practices.

1.1.5 Work methods and work practices

A work method is defined as a "description and specification of the manner in which humans are supposed to execute tasks" (REFA 2023). Alternatively, work practices can be classified as personal scopes of action within a specific work method (REFA 1998), e.g., different manners of operating the machine's boom. Studies reveal that work practices could potentially affect the entire system's productivity (Spinelli et al. 2020, Vasiliauskas et al. 2021). Therefore, work practices are strongly related to single operators. Evaluating individual user profiles is part of current research (Pagnussat et al. 2019), while results of recent studies suggest that the influence of the work practice on whole system efficiency has only been sparsely investigated thus far (see chapter 3.1).

1.2 Problem definition and research objectives

Based on study results, the scientific interest in (new) operator assistance systems on forest machines and the focus on machine operator work practices within fully mechanized timber harvesting is increasing. In general, fully mechanized harvesting systems are mostly investigated with the focus on productivity related to a specific factor, such as slope of the operating terrain or the number of assortments (Ghaffarian et al. 2007, Manner et al. 2013), both for harvesters and forwarders. Some studies have already investigated the effects of operator assistance on productivity of fully mechanized harvesting systems (Manner et al. 2017, Manner et al. 2019). However, these did not focus on the work elements which are actually affected by the assistance systems mentioned, i.e. loading and unloading. Since the loading element covers nearly 50% of the whole forwarder cycle time (Ghaffarian et al. 2007), the focus of two of the three parts (Paper II and III) of the present thesis is set on this work element. Additionally, work practices are only sparsely covered in literature and it remains unclear, how these can be quantified. Therefore, the goal of the thesis is to contribute to the understanding and interpretation of fully mechanized harvesting systems by adding to the list of factors influencing not only productivity, but also machine wear, and overall economic and ecological system performance and to further investigate selected work practices. To this end, three problem statements arise:

1. Work practices seem to affect the overall economic, ecological, and social impacts of fully mechanized harvesting. However, work practices are not clearly defined in scientific literature. Furthermore, the difference between “positive” and “negative” work practices is also not clearly defined.

2. The loading covers nearly 50% of the whole cycle time of the forwarder (Ghaffarian et al. 2007). Scientific literature mentions many factors that affect productivity, mostly measured in produced (felled and processed or forwarded) timber volume per unit time (m^3 per hour). A deep, detailed focus on the loading element itself, while considering different work practices related to loading conditions is missing.

3. The use of operator assistance systems is becoming more common in forestry operations. Some studies investigating the effect of operator assistance on system productivity (m^3 per hour) can be found in literature. However, a detailed focus on the interaction between the forwarder loading element and the use of boom-tip control and rotating cabins is missing. It remains unclear how the use of these assistance systems can affect time consumption per loading cycle, and therefore a great share of overall system productivity.

According to these problem statements, the following research objectives were defined:

1. To address the first problem statement listed above, work practices within fully mechanized harvesting systems will be defined – the focus will be set on harvesters and forwarders. Additionally, positive and negative work practices will be quantified within the context of parameters used to evaluate work practices.

2. To address the second problem statement listed above, a detailed analysis of work practices within the loading element of the forwarder will be done. The effect of different loading distances, loading angles and log orientations on loading productivity of the forwarder (measured in time consumption per loading cycle) shall be quantified. Hence, advice for "best practices" of forwarder operators related to positioning shall be given. Harvester operator work practices will also be evaluated with emphasis on beneficial work practices related to depositing logs for optimal forwarder loading.

3. To address the third problem statement listed above, different forwarder loading scenarios shall be evaluated. The effect of operator assistance systems (Boom-tip control and rotating cabins) on the loading efficiency (time consumption per loading cycle) will be evaluated. Potential beneficial effects of operator assistance on time consumption per loading cycle will help contractors and machine owners apply the optimal machine settings in practice.

To achieve these research objectives, **Chapter 2** firstly presents a summary of the methodological approaches used in the three publications of this thesis. **Chapter 3** aims to give an overview of the results of the three articles, which includes general information on the title, authors (and their related affiliations), journal, and accessibility. **Chapter 4** summarizes the articles' key findings, while **Chapter 5** provides a general discussion of their results and **Chapter 6** a general conclusion.

2. Material and Methods

2.1 Paper I

Citation: Hartsch, F.; Dreger, F.A.; Englund, M.; Hoffart, E.; Rinkenauer, G.; Wagner, T.; Jaeger, D.: Positive and Negative Work Practices of Forest Machine Operators: Interviews and Literature Analysis. *Forests* **2022**, *13*, 2153. https://doi.org/10.3390/f13122153

Methods: In **Paper I**, a two-fold approach was chosen to achieve the objectives described in **chapter 1.2** The methodology included expert interviews and a literature analysis. To gain a detailed insight into forest machine operator work practices, a total of 15 expert interviews were performed in Germany, Norway, and Sweden. Study subjects were forest machine operator instructors, who were selected based on their level of proficiency and experience. A semi-structured approach for the interviews was chosen. An interview guide consisting of ten questions related to machine operator work practices, harvester-forwarder interaction, operator education and -development, and optimization potentials of fully mechanized harvesting systems was developed. The participation was voluntary. The instructors themselves worked with both beginner- and experienced operators. The interviews were conducted between June 2019 and May 2020. The interviews were recorded, transcribed, paraphrased and anonymized (Hartsch et al. 2022 b).

Before analyzing the interviews, a coding system was developed, to refer statements of the interviewees to categories. Firstly, these categories were clustered in relation to scientific literature. Statements of the instructors were then added to types (Harvester, Forwarder, Value, Teamwork, Teaching and communication skills), since these aspects could potentially be affected by work practices. Then, statements were referred to the categories (Harvester: Positioning and reaching for trees, felling, crane settings, crane use, other; Forwarder: Crane settings, crane skill, loading, unloading; Value: Value; Teamwork: Teamwork and psychology). The analysis of the interviews was done using the software MAXQDA v. 12.3.5. After analysis, positive and negative work practices were collected and defined, and then related to practical examples given by the interviewees (Hartsch et al. 2022 b).

For the literature analysis, guidelines according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used. Several scientific databases, such as Scopus and Web of Science, were screened by using Boolean operators. In addition to the online literature search, senior scientists were consulted for recommendations on literature related to forest machine operator work practices. Then, the results of the literature search (2480 journal articles) were processed. This involved removing duplicates and screening journal titles and abstracts for information relevant to the research objectives. To include articles from the literature search into the analysis, they needed to adhere to the following requirements: 1) be part of a peer-reviewed journal (in English), 2) be an empirical study or a structured interview, 3) needed to be related to harvesters, forwarders, and harwarders, and 4) needed to report on operator behavior or work practices, meaning an outcome variable to evaluate work practices needed to be given. Results from these studies were extracted. Work practices were collected, information on the effect of work practices on different variables was given, the machine type and study setting were also noted. After listing all the results, work behavior or work practices were classified and rated as either positive or negative, related to the specific results. The full and detailed collection of the methods used, including the references, can be seen in the methods chapter under **Paper I** (Hartsch et al. 2022 b).

2.2 Paper II

Citation: Hartsch, F.; Schönauer, M.; Breinig, L.; Jaeger, D. Influence of Loading Distance, Loading Angle and Log Orientation on Time Consumption of Forwarder Loading Cycles: A Pilot Case Study. *Forests* **2022**, *13*, 384. https://doi.org/10.3390/ f13030384

Methods: In **Paper II**, a field study was conducted to achieve the objectives described in **chapter 1.2**. To reach these objectives, the trials were set up using a physical forwarder simulator (type: Rottne F10). These simulators differ only slightly from "real" machines: The simulator was mounted on a stationary base and the hydraulics were powered by an electronic motor. Crane reach was 7.5 m. The goal of the study design was to perform standardized, repeatable forwarder loading cycles to gain a detailed view on the loading element itself. Five different loading distances (i.e., distances between the crane pillar and the center of a log within the loading position) were set up (3 m, 4 m, 5 m, 6 m, 7 m). Each loading distance was tested over three different loading angles (45°, 90° and 135° azimuthal to the machine axis). Each loading position was tested with three log orientation angles (45°, 90° and 135° azimuthal to the machine axis). These settings resulted in 45 settings in total – each of which was tested with 10 repetitions (450 loading cycles in total). The loading position on the ground was marked by spray paint and regularly renewed between the loading cycles. The starting position of the boom within the load space was predefined (see methods of Paper II). The operator's work task was to load a log from the loading positions into the load space. The log had a length of 3 m and a mid-diameter of 27 cm. The gripping point on the log was also marked by spray paint (middle of the log) to exclude bias potentially caused by varying gripping points. Time measurements of each loading cycle were taken by a stopwatch, which started when boom speed was > 0 and ended when the log was loaded and boom speed was 0. As backup and reference comparison to the manual time study (Hartsch et al. 2022 a), all cycles were recorded using a Sony HC-V777 camera.

To attain as comparable results as possible, the tested operator needed to have sufficient experience in forwarder loading. One of the operator instructors of the Lower Saxony Forest Education Center in Münchehof served as test operator. He was male, 41 years in age (at the time of the study) and had more than 20 years of experience in operating both harvesters and forwarders. He operated simulators regularly, therefore bias caused by unfamiliar machines or surroundings could be excluded. The study was conducted under a lack of performance pressure to create as controlled loading conditions as possible. The study design did not intend to compare operators, but rather a controlled analysis of the loading element was the focus of the study (Hartsch et al. 2022 a).

Time consumption of 450 loading cycles in total was recorded. The balanced data was processed and analyzed with the software language R (version 4.0.2), interfaced with RStudio (version 1.4.1103). Data on time consumption were first transformed into reciprocal values to receive normally distributed residuals of the linear model which was applied. A linear model and generalized least-squares were used. To consider heteroscedastic distribution among loading angle, a constant variance function was applied. A Shapiro-Wilk test served as a test and confirmation of the normal distribution of the residuals. Loading angle, loading distance, and log orientation, were treated independently, including possible interactions between them. The package {emmeans} was used to estimate least-squares means. The reciprocal response values were back-transformed to attain time consumption per loading cycle in seconds. Pairwise comparisons were performed by applying Tukey´s HSD test. Significance level was set at $\alpha = 0.05$, least-square means were shown under standard error (SE) and confidence limits for 95% interval. The full and detailed collection of the methods used, including the references, can be seen in the methods chapter under **Paper II** (Hartsch et al. 2022 a).

2.3 Paper III

Citation: Hartsch, F.; Schönauer, M.; Pohle, C.; Breinig, L.; Wagner, T.; Jaeger, D. (2023): Effects of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study. *Croatian Journal of Forest Engineering* (accepted for publication).

Methods: In **Paper III**, a further field study was conducted to achieve the objectives described in **chapter 1.2**. Unlike the simulator in Paper II, an eight-wheel forwarder John Deere 1210G was used. A double telescopic crane, “Intelligent Boom Control” (IBC, John Deere) and a rotating cabin featured on this forwarder. The crane reach was 10 m. The selected operator was male, 54 years old and had 12 years of experience in operating forwarders (by the time of the study) (Hartsch et al. 2023).

Similar to Paper II, the goal of the methods used in Paper III was to ensure a consistent analysis of the forwarder loading element with emphasis on operator assistance systems, such as boom-tip controls (IBC) and rotating cabins. The key methodology was adapted from Paper II, but adjusted accordingly. The John Deere forwarder 1210 G operated on flat terrain. 15 loading positions were defined: Three loading angles (55°, 90° and 135° azimuthal and counterclockwise to the machine axis) were tested over five loading distances to the crane pillar (4 m, 5.5 m, 7 m, 8.5 m, 10 m). To ascertain the effect of both operator assistance systems on time consumption of forwarder loading, all loading positions were sampled with four variants: IBC deactivated, rotating cabin deactivated (Variant I); IBC deactivated, rotating cabin activated (Variant II); IBC activated, rotating cabin deactivated (Variant III); IBC activated, rotating cabin activated (Variant IV). The log orientation angle was 90° within all settings. In total, 60 sub-variants could be recorded, with 10 repetitions each, resulting in a total of 600 loading cycles. The loading positions and log gripping position (middle of the log) were marked by spray paint and regularly renewed between the loading cycles. A log of 3 m length and 28 cm mid-diameter was used for loading. Cycle time was defined according to Paper II (start: crane speed > 0; end: crane speed = 0 and log loaded). The boom position in the load space before and after loading was predefined. Time consumption per loading cycle was measured using a stopwatch. After loading, the operator returned the log to the starting position to prepare for the next cycle (Hartsch et al. 2023).

To analyze the data, the free software language R (version 4.0.5), interfaced with RStudio (version 1.4.1103) was used. A linear model was used, which included the variables loading distance, loading angle, and the “treatments” IBC and rotating cabin to show potential interactions between them. These were treated as factors. “Time consumption per loading cycle” was defined as the response variable. Levene´s test was used to test and confirm homoscedasticity of time consumption per loading cycle across groups, as well as the interaction of IBC and rotating cabin. A Shapiro-Wilk test was used to test and confirm the normal distribution of residuals. The package {emmeans} was used to estimate least-squares means. Tukey´s HSD post-hoc test was applied to perform pairwise comparisons between the settings and treatments. Significance level was set at $\alpha = 0.05$. The least-squares means were calculated with standard error (SE) and confidence limits for 95% - interval. The full and detailed collection of the methods used, including the references, can be seen in the methods chapter under **Paper III** (Hartsch et al. 2023).

3. Results

3.1 Publication overview

Paper I

Title: Positive and Negative Work Practices of Forest Machine Operators: Interviews and Literature Analysis

Authors: Hartsch, Florian[1,2,*]; Dreger, Felix A.[3,*]; Englund, M.[4]; Hoffart, E.[5]; Rinkenauer[3], G.; Wagner, T.[2]; Jaeger, D.[1]

Authors affiliation: [1] ***Department of Forest Work Science and Engineering***, Faculty of Forest Sciences and Forest Ecology, Georg-August-Universität Göttingen, Büsgenweg 4, 37077 Göttingen, ***Germany***

[2] ***Forest Education Center***, Center for Forest and Timber Industry, Northrhine-Westfalian State Forest Service, Alter Holzweg 93, 59755 Arnsberg, ***Germany***

[3] ***Leibniz Research Centre for Working Environment and Human Factors***, Department of Ergonomics, Ardeystraße 67, 44139 Dortmund, ***Germany***

[4] ***Skogforsk—The Forestry Research Institute of Sweden***, Uppsala Science Park, Dag Hammerskjölds väg 36A, 75183 Uppsala, ***Sweden***

[5] ***Skogbruketts Kursinstitutt***, Honnevegen 60, 2836 Biri, ***Norway***

[*] These authors contributed equally.

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Paper II

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

Authors: Hartsch, Florian[1]; Schönauer, M.[1]; Breinig, L.[1]; Jaeger, D.[1]

Authors affiliation: [1] ***Department of Forest Work Science and Engineering***, Faculty of Forest Sciences and Forest Ecology, Georg-August-Universität Göttingen, Büsgenweg 4, 37077 Göttingen, ***Germany***

Journal: *Forests*

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Paper III

Title: Effects of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study

Authors: Hartsch, Florian[1,2]; Schönauer, M.[1]; Pohle, C.[1]; Breinig, L.[1]; Wagner, T.[2], Jaeger, D.[1]

Authors affiliation: [1] ***Department of Forest Work Science and Engineering***, Faculty of Forest Sciences and Forest Ecology, Georg-August-Universität Göttingen, Büsgenweg 4, 37077 Göttingen, ***Germany***

[2] ***Forest Education Center***, Center for Forest and Timber Industry, Northrhine-Westfalian State Forest Service, Alter Holzweg 93, 59755 Arnsberg, ***Germany***

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Citation: Citation will be available soon due to the upcoming publication

3.2 Paper I: Positive and Negative Work Practices of Forest Machine Operators: Interviews and Literature Analysis

Authors: Florian Hartsch, Felix A. Dreger, Martin Englund, Even Hoffart, Gerhard Rinkenauer, Thilo Wagner and Dirk Jaeger

Abstract: Variance in productivity of fully mechanized timber harvesting under comparable stand and terrain conditions requires the investigation of the influence of work practices of machine operators. Work practices can vary among operators and may result in a wide range of productivity. Therefore, it is of great interest to identify positive and negative work practices of forest machine operators to improve forest work. For the qualitative analysis of work practices, 15 forest machine operator instructors were interviewed in Norway, Sweden, and Germany in semi-structured interviews. Additionally, a literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was performed. The interviews brought up detailed positive work practices and showed negative examples of machine handling, specifically related to boom operation. The literature review retrieved 2482 articles of which 16 were examined in more detail. The review showed that work practice characteristics were only sparsely covered, however, still overlapped with the work practice recommendations from the operator instructor interviews. Further, the literature search unveiled a scientific knowledge gap related to the quantification of applied work practices. Generally, positive work practices can include using optimal working ranges from 4–6 m, frequent machine repositioning, a matched fit of operator skill and crane speed, and an assortment pile size that matches the maximum grapple loads. Training is recommended to focus on crane control in terms of movement precision and work range adherence whereby the speed-accuracy trade-off should be improved to meet productivity requirements and increase efficiency in forest machine operator work.

Keywords: forest work science; work patterns; work elements; work method; machine operator performance; harvester; forwarder; cut-to-length

3.2.1 Introduction

Highly mechanized timber harvesting systems account for the largest share of total logging, which is approximately 50% in Central Europe (KWF 2010, BaySF 2022). In Scandinavian countries, the share of highly mechanized timber harvesting is much higher (approx. 80%) (Karjalainen et al. 2001). Modern forest harvesters fell, process, and deposit full stems or assortments at the machine operating trail. Forwarders load and convey the assortments to the landing (Väätäinen et al. 2006). The control of these forest machines is highly complex (Gellerstedt 2002) and work tasks in mechanized timber harvesting bear a high mental workload on the operator (Grzywinski et al. 2008). Therefore, operating forest machines requires lengthy training, continuous education, and supervision, throughout the operator’s entire career. On average, up to three years of experience is required after training for a forest machine operator to reach full proficiency (Purfürst 2010). Work studies revealed that even experienced machine operators show productivity differences of up to 40% (Ovaskainen et al. 2004).

In recent years, operating forest machines has changed due to the introduction of new technologies. Sensor-based detection of the machine environment gained importance and opened new opportunities for forest companies (Öhman et al. 2008, Lindroos et al. 2015). Operator assistance systems, such as rotating cabins or boom tip control systems, were developed and are still being improved with the goal of increasing productivity and reducing the mental workload of machine operators (John Deere 2022 a, John Deere 2022 b). More detailed analyses of operator assistance systems have shown that productivity can indeed be increased (Manner et al. 2017, Manner et al. 2019, Zemanek and Filo 2022).

Generally, various factors affect the productivity of highly mechanized timber harvesting systems. These performance-determining factors are extensively studied and include operator-related parameters (Purfürst and Lindroos 2011), stand-, timber- (Belisario and Fiedler 2022), and terrain-related characteristics (Proto et al. 2018), technical requirements (Eriksson and Lindroos 2014), and organizational aspects (Zimbalatti and Proto 2010). Regarding the influence of forest machine operators on productivity, a number of studies have been conducted (Purfürst 2010, Belisario and Fiedler 2022, Purfürst and Erler 2011). However, these studies focused mainly on productivity analyses of the main work elements.

Harvester and forwarder work can be categorized by these work elements. These work elements are divided into Driving/Crane use/Felling/Processing/Manipulation for the harvester (Nuutinen 2013) and Travel empty/Travel loaded/Loading/Unloading (Ghaffarian et al. 2007) for the forwarder, respectively. Studies suggest that the work method and the work practice of the forest machine operators are crucial for overall performance in highly mechanized timber harvesting systems (Ovaskainen et al. 2011, Danilovic et al. 2011, Ovaskainen 2009, Hartsch et al. 2022 a). Due to the interchangeable use in the literature of the terms work practice, work, and work method, it remains unclear how deeply work practices affect the productivity of forest machine operators.

Therefore, in the present study, a work practice is defined in accordance with the German REFA institute (REFA Verband für Arbeitsgestaltung, Betriebsorganisation und Unternehmensentwicklung e.V.) as part of the work process. A work practice considers the operator-related, individual way of carrying out the work process, based on the work method used. The term describes the personal scope of action within the work method, which serves as a basis for a higher performance and improved ergonomics can be achieved (REFA 1998). In some cases, the terms "work pattern" or "working behavior" are used synonymously in the scientific forestry literature.

The definition highlights that the individual way of carrying out timber felling, - processing, and forwarding in highly mechanized harvesting systems depends largely on the skills of forest machine operators. In this context, even personal preferences can influence performance (Olson and Sarter 2000). Individual work practices can be developed within all work elements and affect not only driving skills or operation planning, but also crane operation (Ovaskainen 2009). The literature on the evaluation of work practices is sparse although there is a need to identify favorable and efficient, and conversely, ineffective and mentally demanding work practices of forest machine operators to improve mechanized timber harvesting. Due to the interlaced task structure and multiple factors that can potentially affect the whole system's productivity, the role of these work practices remains unclear and in particular, to what extent personal work practices contribute to the execution and outcome of work. However, it is assumed that productivity differences between machine operators described in the literature are caused by work practices to a significant extent.

In a nutshell, it is essential to assess beneficial work practices that contribute to performance and lead to an increased productivity. Therefore, the present study aims to give an initial overview of the work practices of forwarder and harvester operators, that can have both an impact on productivity and mental strain, but also on the wear and tear of machines. Two methods, interviews with forest machine operator instructors and a scientific literature analysis will serve as the overview of work practices.

3.2.2 Materials and methods

For the evaluation of work practices, a multipronged approach was used to retrieve information on subject matter, expert interviews, and scientific literature. This allowed for coverage of a broad range of work practices and to compare the state-of-the-art in work practices, as reported on in the literature, to those work practices applied in-service, as reported on in the expert interviews.

3.2.2.1 Qualitative content analysis of expert interviews

Step 1—Preparation and conducting of interviews: A total of 15 expert subject matter interviews were conducted in Germany, Sweden, and Norway. To gain insights into details of instructed forest machine operator work practices, a semi-structured approach was used. Due to the complex content of interviews, the number of selected operator instructors was limited to a closed-question format survey. However, the semi-structured interview guideline revealed complex behavioral patterns that are rarely described in the work science literature. The experts in all contributing countries were selected by their expertise and their availability. All interviewees were experienced in operating forest machines and were currently working as instructors. This allowed for a high skill and proficiency level of the operators' analyses of work practices. The forest machine operator instructors interviewed work both with beginner- and experience-level operators. The interviews were conducted between June 2019 and May 2020. Participants consented to participate voluntarily. The interview guideline was developed by researchers from all partnering countries (see Appendix A). A major goal of the guideline was to ensure consistency, meaning that all interviewees were exposed to all relevant questions and thus comparability of answers could be ensured. The interviews were recorded and then transcribed, paraphrased, and anonymized. Next, the transcripts were assigned the first letter of the country and the interview number as a pseudonym (e.g., Germany = G1–7; Sweden = S1–5; Norway = N1–3). Demographic data and experience level of the forest machine operator instructors are shown in **Table 1**. The 15 experts satisfied the experience criteria in all three countries to have at least two instructors and thus perspectives with, similar experience, machine manufacturer collaboration, certification, and multiple instructed machines and operators.

Table 1: *Demographic data of the operator instructor interviews conducted in Germany, Sweden, and Norway (number ranges only apply to present experience).*

Demographic Data	**Germany (G1-7)**	**Sweden (S1-5)**	**Norway (N1-3)**
Sex [numeral; male, female]	7 m	5 m	3 m
Age [numeral; years; range]	40–57	51–61	29–55
Formal certificate as forest machine operator? [numeral; yes, no]	3 yes, 4 no	3 yes, 2 no	3 yes
Formal certificate as forest machine operator instructor? [numeral; yes, no]	4 yes, 3 no	5 no	2 yes, 1 no
Training cooperation with machine manufacturer? [numeral; yes, no]	6 yes, 1 no	2 yes, 3 no	2 yes, 1 no
In contact with other operator instructors? [numeral; yes, no]	6 yes, 1 no	5 yes	3 yes
Experience on harvesters? [numeral; yes, no]	3 yes, 4 no	5 yes	3 yes
Experience on harvesters? [numeral; years; range]	6–10	10–40	5–26
Experience on forwarders? [numeral; Yes, No]	7 yes	5 yes	3 yes
Experience on forwarders? [numeral; years; range]	1–25	1–40	5–13
At the moment operating any forest machine? [yes; no]	6 yes, 1 no	5 yes	2 yes, 1 no
Years as forest machine operator instructor? [numeral; years; range]	5–25	4–25	1–14
How many forest machine operators get trained per year? [numeral; years; range]	8–20	20–90	20–40
How many forest machine operators were trained in career in total? [numeral; range]	40–300	100–3500	25–400

Step 2—Interview analysis: The interview analysis was performed by using MAXQDA v. 12.3.5 software. Following the transcription and anonymization of the data, a coding system was developed to analyze the interviewees' opinion on positive and negative work practices of forest machine operators and also

to guarantee that all relevant comments on the objectives of the study could be included in the analysis.

The coding system can be described as follows: Firstly, categories were roughly clustered deductively using literature prior to analysis. Before and during the analysis, comments of forest machine operator instructors related to the study objectives were then abductively selected first by type [Forwarder, Harvester, Value, Teamwork, Teaching and communication skills], and secondly based on a category itself [Forwarder: crane settings, crane skill, loading, unloading; Harvester: Positioning and reaching for trees, felling, crane settings, crane use, other; Value: value; Teamwork: teamwork and Psychology: psychology]. The categories developed are not exclusively based on work elements, but also on other aspects that are essential for the daily work of a machine operator. While analyzing the material, a brief written summary for every interviewee's verbal comment on a specific category should guarantee a detailed description of a work practice. It formed the basis for evaluating the operator behavior as either positive or negative, in connection to certain work aspects affected by the work practice (productivity, fuel efficiency, mental strain, machine wear and tear, occupational safety, timber value, hydraulic load). While reviewing the categories of behavior, the importance with respect to the severity in affecting the work outcome was reviewed. In addition, strategies for changing negative work practices were integrated to give advice for productivity improvements in modern cut-to-length systems. In the results section, statements were cited by using the interview number as a pseudonym (e.g., G1, S2). In the discussion of results, an integrative cross- sphere discussion approach was used with the goal of summarizing the categories to extract aspects which are important for practitioners.

3.2.2.2 Methods of the literature analysis

Step 1—Scientific literature database search: The guidelines recommended by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach were selected as the framework for the literature analysis (Page et al. 2021). As no previous review on forest machine work practices was available, the focus was set on the scientific databases Scopus, PsychInfo, GreenFile, Engineering Science, and Web of Science. The following search terms and syntax were used: ('forestry' OR 'forest' OR 'harvester' OR 'forest machine' OR 'forest harvester' OR 'forwarder') AND operator AND ('performance' OR 'workload' OR 'behaviour' OR 'work practice' OR 'work method' OR 'productivity' OR 'Skill'). Next to the online literature search, senior scientists were consulted to obtain literature recommendations (cf. Figure 1 grey column).

Step 2—Initial screening criteria of search results: The literature search resulted in 2480 journal articles and reports. Duplicates were removed from the results. The literature search showed low coherence of the retrieved studies of interest. Then, the journal article titles were reviewed. Articles related to other fields such as machine learning or algorithmic behavior, non-forestry harvesters (i.e., agricultural crops), or the analysis of technical properties of the machine while neglecting the operator, were excluded (see Figure 2). In addition, two recommended journal articles were included at this stage to review the procedure.

Step 3—Final inclusion criteria: The inclusion criteria for the literature retrieved from the databases were the following: (1) the article needed to undergo a peer-revision procedure and needed to be published in English. (2) The article was not a review, but rather an empirical study or structured interview. (3) The study concerned forest harvester, forest forwarder, or harwarder. (4) The study reported the behavior of the operator, a work practice or method that relates to operator behavior, and (5) the study reported an outcome variable or recommendation for the given work method or practice used. Full-text articles retrieved from the databases which did not adhere to these criteria were subsequently excluded from the study.

Step 4—Data and result extraction: The data/information of the remaining studies was extracted by (1) determination of the work practice or work method applied, (2) the measured outcome variable that was either workload, performance, skill, or work behavior, (3) the used system/machine (4), and further (5) the setting in which the study was conducted, e.g., a field test or simulator-based study.

Step 5—Results and Analysis approach: All relevant journal articles with the extracted results were listed. Then, the skill/work behavior was classified as either positive or negative with respect to the specific result. This approach resembled the method from the above-described interview analysis.

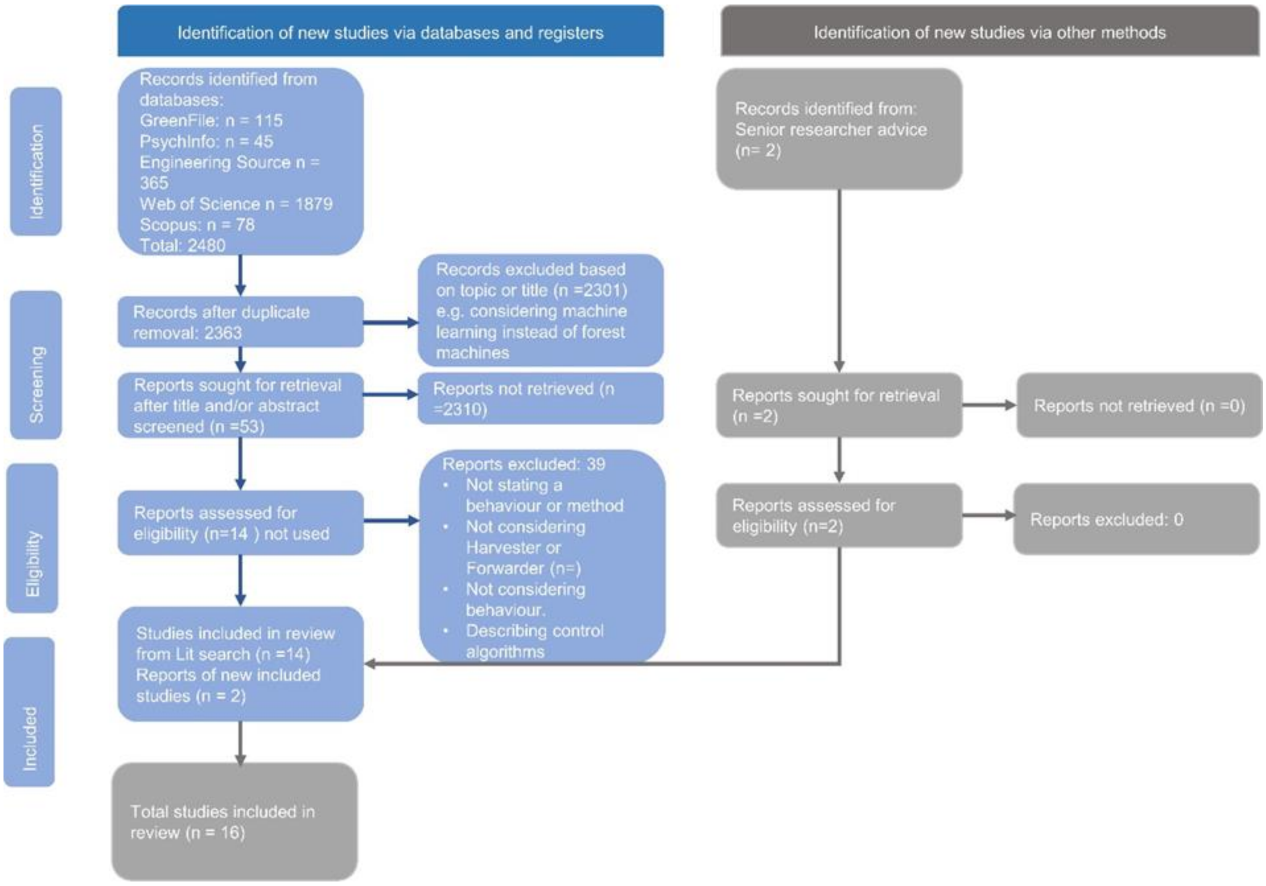

Figure 2: *The PRISMA flow diagram shows the process of searching for and identifying relevant literature for this review (Page et al. 2021).*

3.2.3 Results

3.2.3.1 Results of operator instructor interviews—overview of beneficial and negative work practices of forest machine operators

3.2.3.1.1 Harvester

Positioning and reaching for trees: Operator instructors describe that excessive crane reach (between crane origin and harvester head) is often a problem during both felling and processing, as crane speed and precision decreases, and machine wear and tear increases (S1, S2, S4, N2, N3). As a consequence of this, wood piles become too large and assortments get mixed (S1, S2, S4, S5). When trees are felled in a wide operating range, the stems need to be moved closer to the machine for processing. This affects not only time consumption and mental workload for the operators negatively (N2, N3), but also occupational safety (G1, G3, S1, S5). Another problem is that forest machine operators reposition the machine too infrequently, so that crane paths increase and productivity decreases (N2, N3), which is especially a problem for beginner operators. However, if harvesters are moved or relocated too frequently, this is not optimal, and also affects time consumption (S1, S4, S5). Systematic moving of felled trees from one side of the machine to the other for processing is also frequently observed (S3, S4).

Felling: Forest machine operators often seem to lack a plan in which order to fell trees (S1). Several operator instructors observe that failing to achieve the intended felling direction is a problem too (S2, S3, S4). Based on the interviewees' comments, the first tree to be felled from a harvester's position decides where the pile is placed. Trees are sometimes felled leaning slightly backwards instead of forwards, which means that the operators' view is hidden from the trees' cross-section, hiding potential rot, which negatively influences wood value aspects (S1, S3, N1, N3). While processing, assortment piles should be laid out in a fan pattern. Different assortment piles processed within one harvested stem should touch each other at the machine operating trail facing end but have a separation distance of around 1.5 m at the opposite side (S5) to simplify the consecutive forwarder work.

Crane settings: Forest machine operator instructors notice poorly adjusted cranes (G1, G2, G6). In this context, crane speed is often too high (S2, S5, N1, N2, N3) or too low (N1), which affects productivity, workload, and fuel efficiency.

Crane use: While reaching the tree with the crane, it is sometimes observed that too much tension is put into the tree during felling, which affects timber value, as it induces more cracks in the stem. Furthermore, it is noticed that operators use the extension too late when reaching for a tree. A frequent, unplanned use of the extension is also observed (S1). Forest machine operators also sometimes seem to hold the harvester head too high when processing, which leads to oscillating cranes (N4, S3). After processing trees, harvester operators unnecessarily elevate the harvester head several meters, which negatively corresponds with productivity, workload, fuel consumption, and machine wear and tear (S1, S3). Moreover, if the harvester head grabs the tree too high at the stem to be harvested and not on the stem basis, this leads to correction movements with the harvester head at the stem and can negatively impact the wear and tear of the crane (S1). Other: Forest machine operator instructors mention that weather conditions are sometimes not considered when planning the operation. For example, consideration of wind and felling direction is insufficient (S3). In thinning operations, single crane elements are not observed frequently enough. Too much focus on the head can lead to the crane causing damage to the remaining trees (G1, G2). In addition, it is observed that saw chains are often too blunt, which leads to higher fuel consumption and lower productivity (S2, S4).

3.2.3.1.2 Forwarder

Positioning: Operator instructors from Germany and Sweden confirm that forwarder positioning is a problem while operating the machine. Many operators reach too far with the crane to grab logs instead of moving the machine (G1, G3, S1, S4).

Crane settings: Interviewed operator instructors mention that a disharmony between crane and grapple settings often appears. When closing the grapple, the downward motion of the grapple sometimes does not match the upwards motion of the boom tip from lifting (S1). Operator instructors acknowledge that crane speed should harmonize to “typical” movements. The extension should be used immediately to lift a load and be fully retracted by the time the grapple passes the load space supports. If not, productivity and workload are negatively affected (S2). Full joystick signal to extension in, main boom and slewing should have the logs at an appropriate height over the ground (S4), otherwise this would negatively affect operator workload and productivity. It is observed that operators often operate cranes with too high crane speed (G3, N1, N2, N3, S2, S4), too low crane speed (S2), or that crane settings generally do not fit to the operator (G1, G3).

Crane skill: Especially when beginner forest machine operators work with the crane, they partly perform the movements of the single crane elements non-simultaneously (G1), which affects productivity and fuel efficiency. In addition, crane or joystick movements are mixed up (G4–7). Operator instructors observe that the crane extension is often not used enough or only when a pile cannot be reached without the extension (S2, S3, S4, N3). Operators sometimes forget to pull the extension in and bottoming out the main lift boom instead (G2). Even if Intelligent Boom Control (IBC) is activated, some operators unnecessarily use the extension manually (N3). Continuously holding down “grapple close” while carrying logs is observed as well (S1). After releasing the logs in the load space, the grapple is sometimes closed, which is unnecessary (S1).

Unloading: While unloading, some operators position the grapple too low when opening to release the logs onto the pile, resulting in the grapple pushing on and spreading the logs in the pile. The height at which they open the grapple should account for the space the grapple needs to open (S1, S3). While building a pile, operators should make a succession of peaks and valleys to facilitate the logs falling into place (S4). An incorrect layout of the roadside piles can be observed. The main assortment should be the closest to the access point (S2, S3, S4, N2, N4). Sometimes, an incorrect buildup of piles at the roadside makes the operators lift over the top of the pile. Placing the logs is then more difficult (S1, S2, S4). Some operators do not fill the grapple as much as possible while unloading (S2). While unloading (or loading), operators unnecessarily lift the empty grapple over the supports of the load space, instead of moving through or between the supports, which negatively influences productivity, workload, and fuel consumption (G1, G2, S2, S3, S4, N3). A clumsy release of the logs is also observed. The operators also seem to forget to adjust the height of the boom tip (S2). Mixing assortments is a problem in practice as well. Operators sometimes do not communicate on which assortments to mix in loads (S1, S4). While filling the grapple from the load space, the grapple is often opened too wide. Reaching too wide makes the logs roll over one another, making the load potentially unsafe and disordered. The operators should aim to fill the grapple by reaching deeper into the load (S4).

Loading: Some operators move the machine while having logs in the grapple. This is risky as sudden machine movements can cause the grapple to lose hold of the logs (S2). To ensure flush ends of the grappled logs, some also bump the logs' ends against the ground. This is usually not necessary while loading (S2, S3) and negatively affects productivity. It is observed that forest machine operators start filling the load space against the "cradle". Based on the instructor´s view, it is more productive to start loading against the supports to later allow the logs to fall into the central space (S2, S3). Moreover, sometimes the grapple is not sufficiently filled while loading (G4, S2, S4). Some operators do not want to mix assortments in the load space, which leads to increasing forwarding distances and loading time (N2, N3, S1, S2, S4). Logs are also sometimes gripped at the "wrong" point, which leads to increasing wear and tear and decreasing productivity (S1). A good organization throughout the loading process is often missed. The highest value assortment should be loaded firstly (S1) to keep the option to downgrade logs.

Other: Operator instructors observe that operators do not follow curves in the machine operating trails correctly (G3).

3.2.3.1.3 Value recovery of harvester and forwarder

Value: Regarding the added value of harvesting or forwarding, the influence of various factors is mentioned. Firstly, unbeknownst to the operator, the saw motor could be worn out and not reach suitable rpm, leading to longer cutting times and consequently more cracks in the logs (S2). Secondly, not sharpening the knives of the harvester head (S2, S4) and poor measurements of control logs (calibration) (S2) negatively affect value creation. A blunt chain or not changing a worn-out chain on the harvester head on time is observed as well (S2, S4). Using worn-out feed rollers and compensating for this by pulsing the knives following along the stem with the crane tip can also occur (S4). Aggression with the crane tip while following along the stem is observed (S4), which leads to timber damage.

3.2.3.1.4 Teamwork of harvester and forwarder operators

Teamwork: According to the interviewees, in the context of teamwork, there is often a lack of agreement on a system for how the harvester should stack the assortments. This deeply affects the productivity of the forwarder (S2, S3, N1, N2, N3). Sometimes, harvester operators pile assortments in places with poor ground conditions (wet, sloping), which also negatively affects forwarder productivity (S1, N1). Operator instructors mention that some harvester operators do not understand highly mechanized harvesting systems as teamwork between harvester and forwarder (S2). Additionally, some harvester operators seem to believe that bigger piles are better for forwarder operators. Based on the instructors´ comments, one full grapple per pile is optimal (S1). In contrast, forwarding productivity is negatively affected by the harvester spreading out the logs too much (S3).

3.2.3.1.5 Teaching and communication skills (harvester and forwarder)

The relationship between operator instructor and operator is considered to be highly important to the success of the coaching process. Operator instructors frequently mentioned that the first contact with the operators is important. Firstly, to get the initial impressions of the applied work practices and secondly, of the operators' attitude towards training (i.e., receptiveness). If the opinion of operators on how the machine ought to be operated is considered, they can come up with ideas on which aspects they need to work on, also on a long-term basis (follow-up meetings) (S2). It seems to be important to praise operators when they work well or improve, not only remark on things they should do differently (S2). Recording operators on video is an appropriate way to improve their working behavior (S2, N3). Motivation of operators in exercises is important to improve their productivity in the long-term, since their performance might decrease in the early stages of testing a new work method (S1). To improve productivity, feedback such as that which is available in simulator training, is beneficial (S1). Additionally, testing other crane settings can improve skills while reducing mental workload. This is especially important while teaching younger operators. Setting up the machine and crane correctly so that it fits to the operator is mentioned as a central requirement for a successful training session (N2, N3). When asking operators to try new settings, it is important to give operators the possibility to revert to the original crane settings (S3). Furthermore, when teaching new operators, the most difficult task for the instructors seems to be adapting them to different circumstances (S4). Setting goals and objectives for the operators, which are achievable, are mentioned as well (S5).

3.2.3.2 Results of literature review

3.2.3.2.1 Overview of study layout

Sixteen studies were examined in total (Väätäinen et al. 2006, Ovaskainen et al. 2004, Ovaskainen et al. 2011, Hartsch et al. 2022 a, Spinelli et al. 2020, Bembenek et al. 2020, Vasiliauskas et al. 2021, Ovaskainen et al. 2006, Andersson and Eliasson 2004, Manner et al. 2020, Szewczyk et al. 2021, Eberhard and Hasenauer 2021, Holzleitner et al. 2019, Labelle et al. 2017, Labelle and Huss 2018, Uusitalo et al. 2004). Three out of these studies (Ovaskainen et al. 2011, Spinelli et al. 2020, Manner et al. 2020) were simulator-based studies, and 13 studies were conducted in-field (Väätäinen et al. 2006, Ovaskainen et al. 2004, Hartsch et al. 2022 a, Bembenek et al. 2020, Vasiliauskas et al. 2021, Ovaskainen et al. 2006, Andersson and Eliasson 2004, Szewczyk et al. 2021, Eberhard and Hasenauer 2021, Holzleitner et al. 2019, Labelle et al. 2017, Labelle and Huss 2018, Uusitalo et al. 2004). Simulator studies assessed more participants, whereas field studies range from 1–6 participants. Commonly, field studies depend on specific machines and operators driving on-site. That is why the analyzed studies considered the operators related to a specific machine (e.g., two operators for one machine, working in shifts), as participants. Generally, when reported, the operators that served as participants were experienced and had more than 10 years of experience. Four (Väätäinen et al. 2006, Hartsch et al. 2022 a, Vasiliauskas et al. 2021, Manner et al. 2020) out of the sixteen studies were assessing forwarder work whereas ten (Ovaskainen et al. 2011, Spinelli et al. 2020, Bembenek et al. 2020, Ovaskainen et al. 2006, Szewczyk et al. 2021, Eberhard and Hasenauer 2021, Holzleitner et al. 2019, Labelle et al. 2017, Labelle and Huss 2018, Uusitalo et al. 2004) were concerned with harvester operations, a single study was concerned with a harwarder (Andersson and Eliasson 2004), which is a combined machine of harvester and forwarder. Both thinning and clear-felling operations were the focus of the research. The variables of interest were predominantly productivity and time, but operator workload and tree damage were also assessed.

3.2.3.2.2 Synthesis and evaluation

To identify work practices, behaviors, or skills that were beneficial to the productivity, well-being, or general performance of the system of forest machine and operator, the study outcome was filtered with respect to recommendations or results that can be used to advise and inform machine operators. Then, the results were compiled within the evaluation column of Table 2, which shows that there is a vast range of applicable situations that can benefit from informed operator behavior. The results of **Table 2** will be briefly summarized here. As the machines and methods are highly complex only specific situations, methods, or single work elements were addressed within the analyzed studies. The eleven studies investigating work methods with harvester operators provided the basis of recommendations. Generally, recommendations are found independent of the type of operation (thinning or clear felling). Only one study for piling was found that researched the difference between these general operations in forestry. In thinning operations, beneficial work practices are “right angle piling” and “under the boom piling”, whereas in clear felling (forward felling), “two-sided piling” is applied by the operators (John Deere 2022 a). Efficient work practices for both methods that were identified included: Reducing the number of times the machine drove in reverse, moving the machine frequently and realizing short tree-handling distances to avoid unnecessary boom movements, keeping movements of the stem to a minimum after felling (Ovaskainen et al. 2004), placing edge trees at 1.2 m rear distance to the boom base (Ovaskainen et al. 2006), using automated bucking while processing (in particular in spruce stands), employing a high feeding speed and processing the tree as close to the machine as possible (Ovaskainen et al. 2004), and piling the logs according to the assortments (Väätäinen et al. 2006). Furthermore, long-term productivity was found to be negligible if the forest manager or an experienced operator decided on the tree selection (Eberhard and Hasenauer 2021, Holzleitner et al. 2019). With respect to operator workload and fatigue, we found a study that showed increased tree damage at dawn and at the end of the shift (Bembenek et al. 2020). In addition, workload was found to increase with increased slope and working in mixed stands, compared to monoculture stands (Spinelli et al. 2020, Szewczyk et al. 2021). A single study researched the work method of a harwarder and found driving along the cut edge and processing the tree directly into the load space as the most efficient method (Andersson and Eliasson 2004). The literature search on forwarder operators showed that loading is the primary interest of the retrieved studies. Hartsch et al. (2022 a) found log and loading angles of 45° as most beneficial within a work range of 4–6 m for a certain machine type. Moreover, the grapple load was analyzed in another study, and the assortment pile size should match the maximum grapple load, to ensure efficient handling (Väätäinen et al. 2006). As a new tool, a multiassortment grapple would improve loading efficiency if the remaining trees do not obstruct the trajectory between assortments (Manner et al. 2020). Furthermore, to mitigate the impact of vibrations on the operator while keeping a high efficiency, a driving speed of 8 kph was found to balance well-being and efficiency (Vasiliauskas et al. 2021). Overall, the recommendations on work practices are given within all work cycle elements of forwarder, harwarder, and harvester.

Table 2: *Data extracted from the PRISMA literature review.*

Online Databases						
Study Title	***N***	**Skill, Work Method, Behaviour, Work Practice**	**Outcome Variable, Performance**	**Machine**	**Setting**	**Evaluation**
Hartsch et al. (2022). Influence of Loading Distance, Loading Angle and Log Orientation on Time Consumption of Forwarder Loading Cycles: A Pilot Case Study.	**1**	**Loading logs with forwarder**	• **Loading distance** • **Loading angle** • **Log orientation angle**	**Forwarder**	**Field**	**Beneficial for productivity:** • **45° Log angle** • **45° Loading angle** • **4–6m range**
Vasiliauskas et al. (2021). Driving Speed influence on operator vibration exposure in forwarding operations.	**1**	**Control of driving speed**	• **Driving speed** • **Vibration exposure**	**Forwarder**	**Field**	**Optimal vibration/productivity ratio at 8km/h**
Bembenek et al. (2020). Effect of Day or Night and Cumulative Shift Time on the Frequency of Tree Damage during CTL Harvesting in Various Stand Conditions.	**2**	**Shift-dependent boom control**	**Tree damage**	**Harvester**	**Field**	**Increased tree damage:** • **Dawn** • **End of shift**
Spinelli et al. (2020). The Effect of New Silvicultural Trends on Mental Workload of Harvester Operators.	**13**	**Mental control demand of boom in mixed vs. mono cultivation**	**Workload/ NASA TLX**	**Harvester**	**Simulator**	**Higher workload in mixed stands compared to mono cultivation**
Ovaskainen et al. (2011). Productivity of Different Working Techniques in Thinning and Clear Cutting in a Harvester Simulator.	**5**	**Piling methods in thinning and clear-felling**	**Productivity**	**Harvester**	**Simulator**	**Beneficial work method Thinning:** • **right angle piling** • **under the boom piling** **Clear felling:** • **forward felling** • **two-sided piling**
Ovaskainen et al. (2006). Effect of Edge Trees on	**6**	**Decision of where to leave edge**	**Productivity and distance of Edge tree to boom base**	**Harvester**	**Field**	**Edge trees are best at the roadside 1.2 m from boom base to the rear**

Harvester Positioning in Thinning.		**trees and position harvester**				
Andersson and Eliasson (2004). Effects of Three Harvesting Work Methods on Harwarder Productivity in Final Felling.	**1**	**Three methods of tree cutting and loading**	**Productivity**	**Harwarder**	**Field**	**Most efficient:** **Driving forward along cut edge and process directly in loading area**
Manner et al. (2020). Innovative productivity improvements in forest operations: a comparative study of the Assortment Grapple using a machine simulator.	**4**	**Assortment grapple tested in loading task**	• **Productivity m³** • **Time (s)**	**Forwarder**	**Simulator**	**Assortment grapple is more productive (if movement is not blocked by young stand)**
Szewczyk et al. (2020). The mental workload of harvester operators working in steep terrain conditions.	**1**	**Felling at varying slopes 9%, 23%, 47% assessed**	**Workload measured by eye tracking: fixations and saccades**	**Harvester**	**Field**	**The steeper the slope the greater the workload**
Eberhard and Hasenauer (2021). Tree marking versus tree selection by harvester operator: are there any differences in the development of thinned Norway spruce forests?	**4**	**Fell decision making trees in advance vs. operator while operating**	• **Productivity** • **Forest development**	**Harvester**	**Field**	• **70% concurrency of forest manager vs. operator tree selection.** • **After 50 years sylvicultural differences neglectable**
Holzleitner et al. (2019). Effect of prior tree marking, thinning method and topping diameter on harvester performance in a first thinning operation—a field experiment.	**1**	**Fell decision making trees in advance vs. operator while operating**	**Productivity**	**Harvester**	**Field**	**Tree marking is not relevant factor in tree selection of productivity**
Labelle et al. (2017). The effect of quality bucking and automatic bucking on harvesting productivity and product recovery in a pine dominated stand under Bavarian conditions.	**1**	**Operator manual cuts or automatic, system defined cuts**	**Productivity/ value**	**Harvester**	**Field**	**Automatic bucking beneficial in spruce but not in pine trees compared to manual logging**
Labelle and Huß (2018). Creation of value through a harvester on-board bucking optimization system operated in a spruce stand.	**1**	**Operator manual cuts or automatic, system defined cuts**	**Productivity/ value**	**Harvester**	**Field**	**When thinning in spruce dominated stands, automated bucking is more productive than in pine in stands**
Uusitalo et al. (2004). The effect of two bucking methods on Scots pine lumber quality.	**2**	**Operator manual cuts or automatic, system defined cuts**	**Productivity/ value**	**Harvester**	**Field**	**Automated bucking does not reduce productivity**
Articles from recommendations						

Väätäinen et al. (2006). The effect of single grip harvester`s log bunching on forwarder efficiency.	**6**	**Pile size/ bunching**	**Productivity**	**Harvester Forwarder**	**Field**	• **Piles = max. grapple load.** • **Single pile is to be avoided** • **Adapt method to machine size used** • **Small and Large diameters are to bunch precisely**
Ovaskainen et al. 2004. Characteristics and Significance of a Harvester Operators' Working Technique in Thinnings.	**6**	**Observation of entire work cycle**	**Productivity m³**	**Harvester**	**Field**	• **No reversing** • **Move the machine frequently to adjust work location** • **Short distance to cut -- reducing unnecessary boom movements** • **Unnecessary stem movement while felling should be avoided** • **Processing close to stump** • **High feeding speed in processing**

3.2.4 Discussion

The goal of this study was to identify positive and negative work practices of forest machine operators using two different approaches. One approach used interviews with machine operator instructors in Norway, Sweden, and Germany. The second approach used a literature review of forest machine operator work practices, in accordance with the PRISMA guidelines (Page et al. 2021).

3.2.4.1 Discussion: Interviews

The interviews aimed to get a detailed description and informed analysis of the work practices of forest machine operators for both harvesters and forwarders. An integrative cross-sphere discussion approach for both harvester- and forwarder-related comments was followed to extract the relevant work practices.

The main results of the interview unveiled five key elements that contribute to work practice performance that are discussed below for both harvesters and forwarders.

Positioning the machine: Negative work practices often become evident while positioning the machine. "Negative" positioning, i.e., too far a distance between the machine and the tree to be harvested (harvester), or the wood pile to be loaded (forwarder), leads to increased wear and tear of the crane elements and also to decreased productivity due to longer crane paths. This is in line with other studies which revealed that increasing loading distances can have a negative impact on time consumption per loading cycle (Hartsch et al. 2022 a), and therefore productivity. Since the loading element is the most important (Ghaffarian et al. 2007) to productivity, adequate positioning towards reducing time consumption during loading is worth striving for.

Crane use: A second important aspect is the use of the crane. Both the sequential use of single crane elements and the lack of using the boom extension were identified as problematic ways of working. Based on the instructors´ statements, it can be assumed that these work practices occur particularly with beginners. Accordingly, it could be important to apply training programs such as RECO (economical driving and fuel consumption) (RECO 2022) or state-certified forest machine operator training (Germany). When novice operators control the crane, productivity can be increased by using intelligent crane controls (Manner et al. 2019).

Value: Regarding value-added timber production, forest machine operator instructors highlighted the continuous maintenance of the harvester head and saw chain as a decisive factor. Based on the interviewees´ comments, respondents cited that dull chains increase the machine’s fuel consumption and decrease the value of the produced timber. Furthermore, worn-out feed rollers and the actions operators take to compensate for this introduce errors in the length measurement. There is no literature investigating feed rollers specifically, but forest machine operator instructors report that feed roller maintenance does not receive enough attention in forest operations.

Teamwork: Forest machine operators often do not seem to understand the collaboration between harvester and forwarder as a crucial aspect of overall system productivity. Based on the comments of the forest machine operator instructors interviewed, harvester operators sometimes do not know that the quality of log processing and depositing deeply affects forwarder productivity. When depositing the logs at the edge of the machine operating trail, a pile size corresponding to one full grapple seems to be optimal based on the instructors´ comments. In practice, this likely depends on stand and terrain conditions. Studies have shown that a higher degree of timber concentration along the skid trail generally increases the productivity of the forwarder (Väätäinen et al. 2006). Further, the assortment-related log concentration affects forwarding efficiency (Manner et al. 2013). This shows that the optimal placement of logs by the harvester can mitigate the tedious sorting of different assortments by the forwarder during subsequent loading.

Teaching and communication skills: Operator instructors mention the significance of adaptive teaching and training activities to achieve compliance with the training to increase productivity. In this regard, scientific studies underline that the skills and the aptitude of the forest machine operator affect productivity significantly (Purfürst and Erler 2011). However, task complexity during crane operations can be simplified by using intelligent crane controls (Manner et al. 2017). This suggests that future studies on training should focus on how to cope with the complexity and increase training motivation to support the mental well-being of forest machine operators. Based on the interviewees' comments, the effectiveness of the harvester and forwarder work seems to be related to the freedom and autonomy given to the operator in the design of training and the work task while achieving clear performance goals (see Section 3.1.5).

In summary, the interviews provided detailed insights into challenges in machine operation in terms of specific work practices that are to be avoided and others which should be favored by the operators. Forest machine instructors highlighted negative work practices that they encounter in their daily work. In contrast, "beneficial" work practices were partly inferred from non-negative behavior. Interviewees could hardly determine quantitatively the general impact of the work practices on productivity or machine wear since work practices need to be assessed within their context. Thus, the impact on system productivity must be seen within the interaction of the individual machine operator and other performance-determining factors (i.e., environmental). Compared to interviews, large-scale surveys with sufficient sample size could produce statistically more accurate and representative results (Negro et al. 2021). However, because neither the number of forest machine operators in Germany, Norway, and Sweden is known nor the research field of forest machine operator work practices has been researched in detail, it was decided to conduct subject matter expert interviews. It can be assumed, despite the limited number of interviewees, that the results have practical relevance, precisely because of the years of experience and the number of trained operators.

3.2.4.2 Discussion: Literature search

The literature search was aimed to allow for a comparison with the actual applied practices and enrich and validate reported work practices from the interviews. Research studies on operator work practices unveiled room for improvement of productivity in all work elements. According to the studies analyzed, Forwarder operators ought to focus on diligent execution of the loading cycle, raising efficiency, and should be meticulous in assortment handling, namely the separation and size of piles.

Harvester operators need to realize short tree handling distances and therefore improve on machine driving and efficient boom trajectories to ensure a short work range (see Table 2 above).

The studies included in the review are a glimpse into the diverse range of work practices that are applied by the operators in the field (see also Section 3.1). The number of studies included in the review was surprisingly limited, despite having a broad range of search terms. Only a few studies investigated a specific work practice independent of new technical systems. This may lie in the research foci of the field of forestry work science, where the effect of operators' work patterns or method execution on productivity is less researched than equipment and machine advancements. The studies that were excluded from the review research timber harvesting on a broader scale than on the level of the work practice of the individual operator. The small number of studies found on optimal boom control, driving, and positioning of the harvester is showing that there is still a huge potential for analyzing the efficiency of specific work practices. In general, the included studies suffered from small sample sizes, which is common in the forestry sector due to limitations in access to machine operators. Therefore, some of the recommendations within the research are based on expert opinions. Still, the review unveils efficient work practices that can be used to inform operator support, training, and further increase the resource efficiency in timber harvesting.

3.2.4.3 Literature review and interview result synthesis and limitations

The interviews and the literature review showed overlapping results with respect to crane control, assortment piling, and assortment handling of harvesters and forwarders. For instance, keeping tree-handling distances short, within a range of 4 to 6 m, is good practice, as well as piling assortments in sizes matching the capacity of the grapple. Notably, there is a large difference in the number of work practices described by the operator instructors and the ones found in the literature. Within the interviews, instructors elaborated in fine detail on many work practices they observe in the field and instruct. Specifically, the forest machine operator instructors made detailed statements on the relation between working ranges, optimal machine (re)positioning, appropriate crane settings, best practice training concepts, and adequate machine maintenance. This information cannot or only rarely be found in the literature. The literature review results revealed a vast knowledge gap on the detailed description and specifically, the quantification of work practices. In line, the literature covered a small range of practices; not many studies covered each element of the work task and thus lacked in-depth analyses. The shortage of evidence needs to be enriched to bolster the statements of operator instructors with quantitative data.

In this regard, the interviews shed light on a large amount of advantageous and disadvantageous work practices that are not or insufficiently described in the scientific literature, such as the effect of the felling direction on processing and log piling. Herein, the interplay of reaching distance and repositioning of the machine or the advantages of fan patterns of piles, pile sizes, locations, or loading angles on forwarding efficiency or operator strain (see Section 3.1.1.) remain to be supported by scientific evidence. Furthermore, the negative effect of improper crane settings on wear and tear, fuel efficiency, value recovery, and the operators' mental load needs to be determined. In line, the effects of the consequences such as additional stem relocation or failure to control for rot while bucking due to visual obstruction cannot be found in the scientific literature, although play an important role in practice according to the instructors. The future challenges of forest research lay in the interaction of work practices such as the above example of the felling direction and the processing location on the operator task level, but also in the demand imposed by the triad of task, machine, and work environment. Altogether is known to reduce efficiency, where the extent of each of the work practices requires thorough quantification.

For system design, we encourage next to the recent automation advances such as boom-tip controls to ease the precision motion of the crane including operator recommendations, e.g., on stem handling. Operator training can be improved with a focus on the interaction of the work phases whereby enhanced crane efficiency needs to be trained considering the advantages of proper positioning, but also on a higher goal level with the focus on low-wear handling of forestry machines. Currently, machine operator training is based on the experience of the instructors, which contributes to the present study by giving a detailed view on work practices which potentially optimize the work system. The complex and diverse emerging picture of advantageous and disadvantageous work practices goes beyond conventional training (and the above-cited scientific literature), which is often based on national education curricula that may diverge for countries, vary in the applied methods, and is inaccessible to the broader scientific community. Nonetheless, the link between the interview results to real-world operations can be considered accurate and relevant since instructor recommendations come directly from application and show overlap with scientific studies (Ovaskainen et al. 2004, Hartsch et al. 2022 a). Despite the individual instructor views in three different countries, coherent statements on work practices across Norway, Sweden, and Germany were found. However, a full representative coverage despite a thorough conduct cannot fully be ensured with 15 interviews. That is why a few groups or categories are built on a few coherent statements.

3.2.5 Conclusions

Work practices can be described as the machine operators' implementation style of a given work method, that affects system productivity and machine wear and tear. However, the instructors´ descriptions of work practices are based on subjective observations of forest machine operators. When setting goals for work practice optimization, the instructors usually refer to machine positioning, crane work, value creation, teamwork between harvester and forwarder, as well as motivation and stress. Due to the high level of experience of the interviewed forest machine operator instructors and overlap with the scientific literature, a practical relevance can be assumed.

Although work practices can also be defined by means of the literature, the number of studies found was rather small and touched upon few but distinct task domains of machine operator work. Although there are extensive studies on the influence of the machine operator on system productivity, a large proportion of the studies reviewed examined the effects of a specific factor on productivity. Few studies considered also forest development or mental strain.

This study combined a thorough literature review and the analysis of 15 exploratory interviews to investigate an almost untouched field of forest research—the forest machine operator work practices and their potential effect on system productivity, fuel consumption of forest machines, and machine wear and tear. There is a plethora of factors that potentially affect harvester and forwarder productivity, with the human operator at the heart of the operation. Due to the extensive challenges associated with establishing both ecologically considerate and scientifically valid laboratory conditions in forest operations research, the evidence of the actual effect of specific work practices still needs to be investigated further. However, previous studies including exploratory interviews suggest that work practices may have a strong impact on productivity and machine wear and tear. Technical developments that ease machine control, the shortage of labor, and new silvicultural requirements due to climate change urge to set an increasing focus on operator performance in work systems, despite the introduction of automation. Efficient work practices are essential for future mechanized timber harvesting and ought to be addressed in research to raise the quality of operator training and support system design. By that, the research line of work practice performance may unlock new productivity potential of mechanized timber harvesting.

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Data Availability Statement: To keep anonymity of the interviewees, public accessibility of the interviews is not given.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A1

Table 3: *Interview guideline with ten main questions.*

No.	Question(s)
1	What are the most common/important problems that machine operators have with their driving skill/work method/work practice?
2	Can you give an example where you have helped an operator develop the driving skill/work method and made it a big difference?
3	Is the problem describable with machine data (angle, speed, position,…)?
4	What aspects of work are mainly affected (mental/physical workload, productivity, value preservation, safety, soil impact…)?
5	How big are the effects? How common is the problem?
6	How do you notice this problem? What indicators is it that you observe?
7	What strategy do you have to help the operator improve this aspect? What difficulties or obstacles can there be for the operator to change or improve?

8	Skill and work method relationship (Does the skill level affect which work method the operator uses? Do some work methods require more skill than others?)
9	Harvester affecting forwarder (What problems with the harvester work method/skill has the most effect for the forwarder? What effect?)
10	Crane settings (What are the consequences of a poorly set up crane? How do you notice? What are the most common/important problems with the settings?

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

Authors: Florian Hartsch, Marian Schönauer, Lorenz Breinig and Dirk Jaeger

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

3.3.1 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 (Nurminen et al. 2006) due to its high productivity (Dvorak et al. 2008) and high occupational safety (Axelsson 2013). In Germany, between 50 and 60% of the timber is felled and processed by harvesters (KWF 2010, BaySF 2022, Karjalainen et al. 2001, Hoffmann and Jaeger 2021), which results in lower amounts of damages to the remaining stand as compared to motor-manual felling (Spinelli et al. 2004). 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 (Väätäinen et al. 2006). The productivity of a harvester depends largely on the characteristics of the forest stand and terrain (Mederski et al. 2016). 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 (Tervo et al. 2010, Palmroth 2011, Purfürst and Lindroos 2011, Manner 2021)), 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 (Nurminen et al. 2006, Väätäinen et al. 2006, Manner et al. 2013, Proto et al. 2018; (II) stand and timber characteristics such as the stem volume (Acuna and Kellogg 2009) or the number of assortments (Manner et al. 2013, Gingras and Favreau 2005, Bodelschwingh 2006, Eriksson and Lindroos 2014); (III) terrain-related factors such as slope (Ghaffarian et al. 2007, Strandgard et al. 2015) or the extraction distance (Proto et al. 2018, Bodelschwingh 2006, Eriksson and Lindroos 2014, Ghaffarian et al. 2007, Strandgard et al. 2015, Tiernan et al. 2004); (IV) technical parameters such as the loading capacity of the machines used or track support (Proto et al. 2018, Eriksson and Lindroos 2014, Tiernan et al. 2004) ; and (V) general organizational aspects (Zimbalatti and Proto 2010), such as the harvested volume per area (Bodelschwingh 2006) , and, in this context, the total harvesting volume (Mederski et al. 2016) or restrictions related to forest management (Stankic et al. 2012, Gerasimov et al. 2012), e.g., silvicultural objectives (Eliasson et al. 2020). Indirectly, even the frequency of maintenance influences productivity as it affects the duration of downtime (Kovac et al. 2021). 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 (Manner et al. 2013, Holzfeind et al. 2018). Of the total forwarding cycle time, 45% and more can be assigned to the loading element (Väätäinen et al. 2006, Manner et al. 2013, Ghaffarian et al. 2007, Manner et al. 2016) and operating the boom can occupy nearly 75% of the loading element itself (Manner et al. 2016). The work method forest machine operators apply in crane work strongly affects productivity (Ovaskainen et al. 2011). 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 (Väätäinen et al. 2006, Manner et al. 2013). 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 (Väätäinen et al. 2006). 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".

3.3.2 Materials and methods

3.3.2.1 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 3**, see **Table 4** 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 3: *Rottne-F10-based forwarder simulator used in the study (Image: Hartsch).*

Table 4: *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

3.3.2.2 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 4a**). 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 4b**). 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.

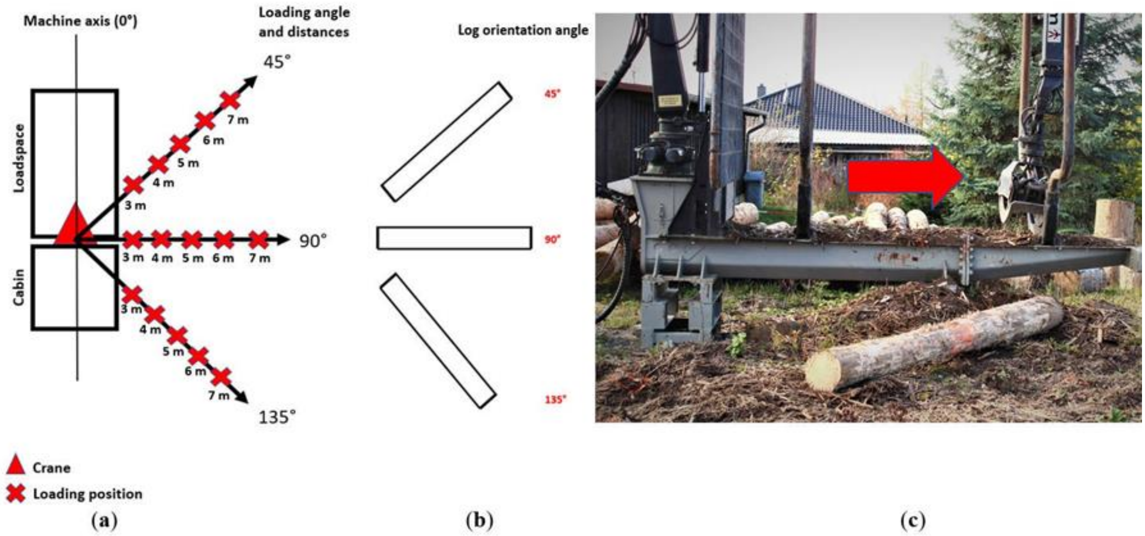

Figure 4: *Study setup: (a) loading distances and loading angles; (b) different log positions; and (c) start position of boom before loading cycles.*

3.3.2.3 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 4c**. 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 m3). 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.

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.

3.3.2.4 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, (R Core Team 2020)), 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 α = 0.05, and least-square means are given with their standard error (SE) and confidence limits for a 95%-interval.

3.3.3 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 5**).

Table 5: *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

3.3.3.1 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 6**.

Table 6: *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

3.3.3.2 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 7**.

Table 7: *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 5**).

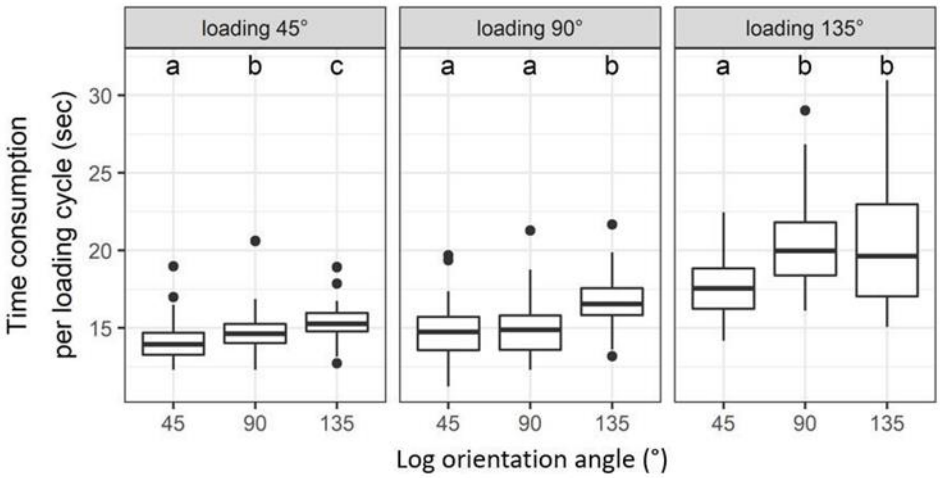

Figure 5: *Distribution of time consumption per loading cycle for three log orientation angles and three loading angles.*

3.3.3.3 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 8**). 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 8: *Least-squares means of time consumption required for loading cycles of each loading distance.*

Loading Distance	Estimated Mean Time	SE	df	Lower CL	Upper CL	Group
3	17.0	0.16	405	16.7	17.3	a
4	15.0	0.12	405	14.8	15.3	b
5	15.4	0.13	405	15.1	15.6	b
6	15.9	0.14	405	15.6	16.2	c
7	17.4	0.17	405	17.0	17.7	a

These patterns could be observed for all three loading angles, whereas ranges be- tween mean values for each distance differed. Groups with dissimilar lower-case letters indicate significant differences according to a Tukey-HSD post hoc test (**Figure 6**). 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.

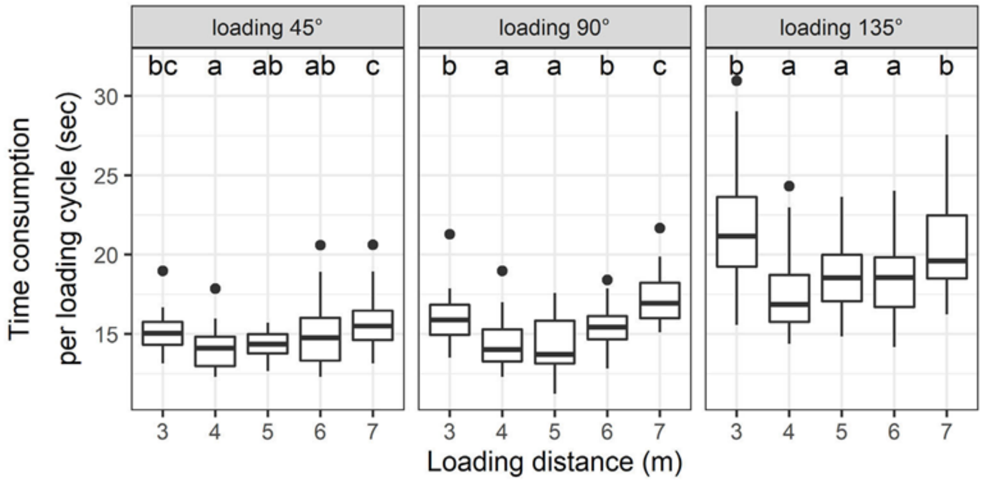

Figure 6: *Boxplots showing time consumption per loading cycle for five different loading distances (m) and three different loading angles (°).*

3.3.3.4 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 7**.

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 7**). Under a loading angle of 135°, averages of increasing time consumption ranged between 40% and 75%.

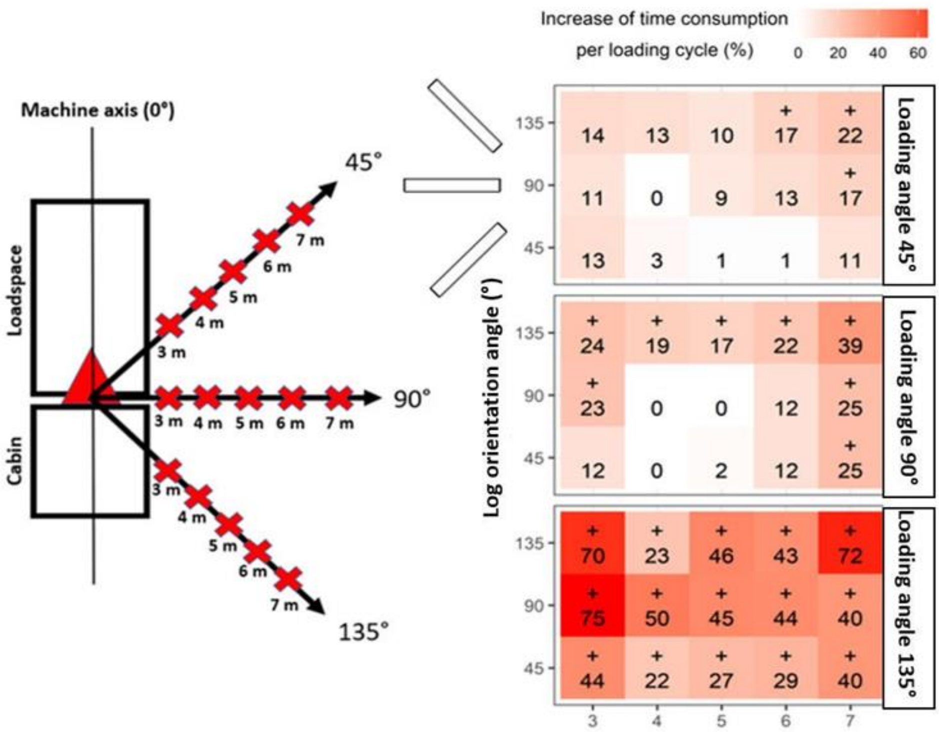

__Figure 7:__ Relative increase of time consumption for loading cycles according to all test settings and reference value ('0').

3.3.4 Discussion

3.3.4.1 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 lay- out 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 for- warders 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. How- ever, 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 (Väätäinen et al. 2006). The methodology did not consider obstacles such as remaining trees, which probably affect time consumption per loading cycles (Geiger et al. 2021). 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 (Ovaskainen 2005). 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 (Jacke and Wagner 2002).

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 ma- chine operator. However, it can be assumed that the different grapple position at the be- ginning 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 de- pending 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 (Lamminen et al. 2011, Manner et al. 2020). According to a long- term study, productivity differences of up to 37% can be explained by an operator effect (Purfürst and Erler 2011). 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 (Manner 2021, Jacke and Wagner 2001). 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 for- warder, 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.

3.3.4.2 Influence of loading angle on time consumption

Results showed significant differences in time consumption per loading cycle be- tween 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 ma- chine operator had to carefully pull the logs out of these positions with the boom tip, be- fore 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 inter- mediate 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.

3.3.4.3 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 un- familiar 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 (Gellerstedt 2002).

3.3.4.4 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 grip- ping 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 (Purfürst and Lindroos 2011). 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 (Lamminen et al. 2011, Ovaskainen et al. 2004). Additionally, operators who spend a smaller share of total time driving due to better skills in positioning the machine, attain better productivity (Väätäinen and Lamminen 2014).

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 (Manner et al. 2020).

Despite the number of previous studies on factors affecting forwarder productivity (Proto et al. 2018) and since other regions of the world have an even higher level of mechanization in timber harvesting (Gerasimov et al. 2008), it is worth taking a deeper look at further relevant aspects deter- mining 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 (Häggström and Lindroos 2016). Other studies have shown that also diverse and more complex forest ecosystems strongly affect productivity, as these affect the mental workload on the operators (Spinelli et al. 2017), which could be examined for the forwarder as well. Through automation of work processes interlinked with digitalization (Lindroos et al. 2017, Müller et al. 2019), 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 (Manner et al. 2017, Manner et al. 2019), in particular since the telescope no longer needs to be operated separately any- more (John Deere 2022 b, Komatsu 2022, Ponsse 2022).

3.3.5 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 for- warder 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.

Author Contributions: Conceptualization was carried out by F.H. and D.J.; Methodology was developed by F.H. and L.B.; formal data analysis was conducted by M.S. and F.H.; F.H. and M.S. wrote the original draft. The article was reviewed and edited by all contributing authors. The research was supervised by D.J. and L.B. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all persons involved in the study.

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3.4 Paper III: Effects of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study

Authors: Florian Hartsch, Marian Schönauer, Christopher Pohle, Lorenz Breinig, Thilo Wagner, Dirk Jaeger

Abstract: Climate change and associated heat waves and droughts are causing enormous amounts of damaged wood in Central Europe. To face these challenges, mechanized timber harvesting systems consisting of single-grip harvesters and forwarders are commonly employed due to their high productivity and work safety. Despite the advantages of these work systems, the operation of advanced forestry machines requires lengthy training and entails high levels of mental strain for machine operators. In recent years, operator assistance systems have been installed in forest machines with the intention of reducing mental workload of machine operators, thereby improving productivity. However, knowledge of the actual effect of operator assistance systems on productivity is still lacking.

The present case study surveyed the effect of two recently released operator assistance features, Intelligent Boom Control (´IBC´) and a rotating cabin (´RC´), on productivity during loading cycles, by means of a time study. Therefore, IBC and RC were tested in different loading settings using a forwarder, John Deere 1210G. Three loading angles were tested (55°, 90° and 125° azimuthal and counterclockwise to the machine axis) in combination with five loading distances (4 m, 5.5 m, 7 m, 8.5 m, and 10 m distance from the crane pillar). The 15 loading positions were sampled using four variants (I: IBC off RC off, II: RC on IBC off, III: IBC on RC off, IV: IBC on RC on), capturing 10 replications for each position and variant, resulting in 600 loading cycles in total.

When the operator was not supported by any system, mean time consumption per loading cycle amounted to 20.6 ± 0.114 sec. The utilization of IBC resulted in a significant reduction in time consumption of 2 seconds per loading cycle. Moreover, further time savings were observed when IBC was engaged in combination with a rotating cabin, leading to a mean time consumption of 17.8 ± 0.114 sec (or 14% improvement) per loading cycle. Although the lowest time consumption was observed when IBC and RC were engaged, the usage of RC alone did not show any significant time improvements.

Since loading activities occupy approximately 50% of the total cycle time in timber forwarding, potential time savings within this work element are crucial for further improvements of work productivity. This pilot case study quantified the time savings when IBC and RC were engaged during

loading in an experimental setting. The results can be used as a basis for further investigations dealing with factors influencing the productivity of highly mechanized timber harvesting systems.

Keywords: Forest Work Science; Time Study; Mechanized Harvesting; Cut-to-length; Forest Operations; Forwarding

3.4.1 Introduction

Central European forests are currently strongly affected by bark beetle calamities as a result of extreme drought in recent years (BMEL 2021a). At the moment, salvage logging makes up around 75% of the total annual harvest in Germany (Destatis 2021). Extensive logistics challenges burden the German forest industry (BMEL 2021 b). Due to high occupational risks, damaged stands are often no longer entered by motor-manual loggers, even though motor-manual logging still plays an important role in German forestry (KWF 2010, BaySF 2022). Highly mechanized harvesting systems are extensively used due to both high system productivity and high occupational safety (Dvorak et al. 2008, Axelsson 2013). In Germany, around 50% of the total volume of timber is processed highly mechanized (BaySF 2022, Labelle et al. 2017, Karjalainen et al. 2001), and probably even more at the time of publication of this study (Hoffmann and Jaeger 2021), with harvesters felling and processing the timber, and forwarders extracting it to the landing.

The productivity of such cut-to-length (CTL) systems is influenced by a variety of parameters, especially operator-related (Tervo et al. 2010, Palmroth 2011, Purfürst and Lindroos 2011, Manner 2021), stand and timber characteristics (Manner et al. 2013, Acuna and Kellogg 2009, Gingras and Favreau 2005, Bodelschwingh 2006, Eriksson and Lindroos 2014; Belisario et al. 2022), terrain-related factors (Proto et al. 2018, Bodelschwingh 2006, Eriksson and Lindroos 2014, Ghaffarian et al. 2007, Strandgard et al. 2015, Tiernan et al. 2004), technical parameters (Proto et al. 2018, Eriksson and Lindroos 2014, Tiernan et al. 2004), and general organizational aspects (Zimbalatti and Proto 2010). In this context, improvement potential in work processes can be observed during collaboration of harvester and forwarder work, e.g. depositing of processed timber along the machine operating trail for effective forwarding (Väätäinen et al. 2006). Therefore, detailed examination of single work elements andpractices is suggested, and is currently the subject of scientific research (Hartsch et al. 2022, Hildt et al. 2020). Several studies revealed that the influence of individual operator performance on the productivity of such CTL systems is highly significant (Purfürst 2010, Purfürst and Erler 2010, Purfürst and Lindroos 2011). Consequently, operator support systems in both scientific research and forest machine development has experienced increased focus (Lindroos et al. 2017, Manner et al. 2017, Manner et al. 2019).

Assisting operators with technical support is a common and established, but still evolving practice in the automotive industry (Bengler et al. 2014, Ziebinski et al. 2017, Köller and Hensel 2019, Kryzanowski 2021). Operator assistance, GNSS and digitalization have also been playing a role in forestry for several years (Zimbelman and Keefe 2018, Müller et al. 2019, Picchio et al. 2020, Latterini et al. 2022), as work tasks in modern timber harvesting systems require great mental strain (Grzywinski et al. 2008). Operator assistance increases safety, overview and efficiency and therefore reduces mental strain as well (Bendel 2021). Based on previous studies, operator assistance can be separated into six levels of automation; from driving without assistance to full automation with machine learning (Lindroos et al. 2017). In the forestry sector, operator assistance and automation processes are of increasing importance (Visser and Obi 2021). Already in the early 2000s, surveillance of machine operating areas was tested in forestry applications (Bombosch et al. 2003), and has since seen steady development (Lindroos et al. 2015, Öhman et al. 2008). Today, operator assistance in forestry focuses not only on logistics planning and optimization (John Deere 2022c, Pellegrini et al. 2013, Contreras et al. 2016) or the application of sensor technology (Picchio et al. 2019), but also on crane work and cabins, as individual operator performance, mental workload and human-centered optimization approaches of operations moves steadily into focus (Spinelli et al. 2020, Szewczyk et al. 2020, Holzinger et al. 2022).

To ensure higher productivity and better ergonomics, different machine manufacturers developed boom-tip control systems (John Deere 2021, Ponsse 2022, Komatsu Forest 2022). Such crane controls simplify the operation of the boom. While using Intelligent Boom Control (´IBC´, manufactured by John Deere company), control inputs are simplified by automatically controlling the extension (Manner et al. 2019). Studies revealed that the application of IBC can improve productivity (Manner et al. 2019) and decrease training extent for less experienced operators (Manner et al. 2017). In addition, a rotating cabin (´RC´) is considered state-of-the-art technology in modern CTL-systems. The rotation of the cabin is realized automatically by a motor, but can be deactivated if necessary (Paakkunainen 2015). Even if IBC and RC seem to improve operational efficiency, a high share of private contractors does not commonly use these systems, so far.

The effect of the application of operator assistance on the productivity of highly mechanized harvesting systems is the subject of current research, where the loading element is of particular interest (Manner et al. 2017, Manner et al. 2019, Zemanek and Filo 2022). One loading cycle is defined as the time duration from a predefined boom position in the load space until the deposition of the log in the load space. Since the loading element occupies nearly 50% of the entire extraction time in forwarding cycles (Ghaffarian et al. 2007), and with the goal to identify improvement potential in terms of loading conditions in forwarding operations, the objective of this study was to analyse the ability of intelligent cranes and rotating cabins to reduce time consumption of loading cycles. The following research questions were addressed within this study:

1. How does the use of IBC and RC affect time consumption of forwarder loading cycles?

2. Are there any interactions between the use of IBC and RC and different loading settings?

3. Can areas of the loading cycle be identified, where time savings due to IBC and RC peak?

In this study, 600 loading cycles were captured by means of a time study in an experimental setting, comprising of three loading angles and five loading distances. Time consumption per loading cycle was compared between the variants IBC (on/off), in combination with RC (on/off).

3.4.2 Materials and methods

3.4.2.1 Machine and operator

The time study was conducted with an eight-wheel John Deere 1210G forwarder (**Figure 8**). The machine was equipped with a double telescopic crane, Intelligent Boom Control (IBC), and a rotating cabin (**Table 9**).

Figure 8: *John Deere Forwarder 1210 G used in the study (Image: Hartsch).*

Table 9: *Technical details of the crane used in the study (John Deere 2016).*

	unit	
Manufacturer		John Deere
Model		CF7
Max. boom range	m	10
Gross lifting torque	kNm	125
Swing torque	kNm	32
Swing angle	°	380
Opening width (grapple)	m	1.82
Gripping area (grapple)	m²	0.95

The operator selected for the study was a forest machine operator instructor (male, 54 years old, 12 years experience in operating forwarders) at the Forest Education Center of the Northrhine-Westfalian state forest service.

3.4.2.2 Study, settings and variants

To ensure a precise analysis of the loading work element in interaction with the operator assistance systems tested, it was decided to conduct a time study focusing on measurements of time consumption per loading cycle. The key steps applied in methodology were similar to a previous case study on the loading work element (Hartsch et al. 2022 a), but were adapted to achieve the specific objectives of this study.

During the study, the forwarder was operated on flat terrain from a fixed position. In total, 15 different loading positions (settings) were defined in a typical working range (**Figure 9**). These included three loading angles (55°, 90° and 125° azimuthal and counterclockwise to the machine axis). For each loading angle, five loading distances to the crane pillar were set (4 m, 5.5 m, 7 m, 8.5 m, 10 m) (Figure 2). At each of the 15 different loading settings, four treatments (**Table 10**) were applied. To clearly illustrate the interaction of the different combinations of operator assistance systems (variants) and time consumption per loading cycle, letters "T" (true) and "F" (false) were used to show whether the systems were activated or deactivated during the measured loading cycles. For each loading position and variant, 10 loading cycles were captured (i.e. 600 loading cycles in total). Consistency of visibility of the loading positions was ensured by repeatedly marking the positions on the ground using spray paint.

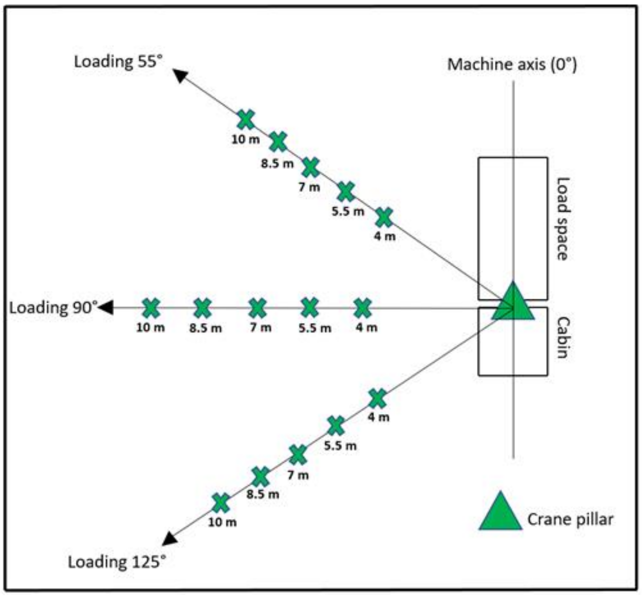

Figure 9: *15 different loading settings with John Deere Forwarder 1210 G, indicated by green ´x´.*

Table 10: *Different test variants applied with each of the 15 different loading settings.*

Test Variant	IBC	Rotating Cabin
I	Deactivated (F)	Deactivated (F)
II	Deactivated (F)	**Activated (T)**
III	**Activated (T)**	Deactivated (F)
IV	**Activated (T)**	**Activated (T)**

Loading angles and loading distances to the crane pillar were determined using a compass and a measuring tape. It was assumed that loading a grapple full of logs would have led to an increased variance and error rate of time consumption per loading cycle as operators in practice, depending on the concentration grade of logs along the skidtrail, need to merge the logs to fully use the capacity of the grapple (Väätäinen et al. 2006). Therefore, and as the study intended to focus on the loading work element, it was decided to load only one 3 m log per cycle. At each loading position, the log (length = 3 m, mid-diameter = 0.28 m) was positioned perpendicularly (90°) to the machine axis. The middle of the log was marked by spray paint to designate the gripping position on the log to avoid bias caused by varied gripping position between loading cycles. One loading cycle included the duration from a predefined boom position in the load space until the deposition of the log in the load space (**Figure 10**). A stopwatch (accurate to hundredths of a second) was used to measure loading cycles, which started when the boom movement for loading the log was started and stopped by the operator. After time measurements were taken, the operator was instructed to reposition the log either in the same loading position (if 10 repetitions were not reached for the setting yet) or in the next one, and to prepare the boom for the next loading cycle. Footage of all loading cycles was captured to allow for subsequent analysis and verification.

Figure 10: *Forwarder at start (left) and end (right) of loading cycle.*

3.4.2.3 Statistical analysis

Data were available for 600 loading cycles in total. The data were analyzed using the free software language R (version 4.0.5, R Core Team 2020), interfaced with RStudio (version 1.4.1103, RStudio, PBC, Boston, MA, USA). The response variable "time consumption per loading cycle" TCL was fitted using a ´full´ linear model, including all available variables; loading distance, loading angle, as well as IBC and RC as dummy variables and potential interactions between. The independent variables were treated as factors due to distance-specific patterns of time consumption per loading cycle (Hartsch et al. 2022). Homoscedasticity of TCL across groups according to levels of the independent variables, as well as the interaction of IBC and RC was tested for and confirmed by Levene's tests. Normal distribution of the residuals was tested and confirmed by means of a Shapiro-Wilk test. Least-squares means were estimated using the package {emmeans} (Lenth et al. 2019). Pairwise comparisons were conducted between each setting and treatment {package: multComp} (Hothorn et al. 2008) using Tukey´s HSD post-hoc test. Visualization (graphing) was performed using {package: ggplot2} (Kassambara et al.

2020). The significance level for all tests was set at α = 0.05, and least-squares means were calculated with their standard error (SE) and confidence limits for a 95%-interval.

3.4.3 Results

3.4.3.1 Overall time consumption per variant and setting

The time study revealed an average time consumption per loading cycle (TCL) of 19.5 ± 0.11 seconds across all settings tested. Mean TCL per setting and variant ranged between a minimum of 14.6 ± 0.935 seconds, observed when loading was carried out from a distance of 4 m and at a loading angle of 55°, with IBC and RC activated, to a maximum of 22.3 ± 1.477 seconds, when loading was done at 10 m, under 55°, with rotating cabin (RC) activated, but "Intelligent Boom Control" (IBC) deactivated.

To test for statistically significant differences of TCL between the settings and variants, a linear model was chosen, integrating the independent variables IBC and RC, as well as loading distance and loading angle. All predictors were found to be highly significant, with loading distance possessing the highest explanatory power in the regression (Supplementary information A1). The application of both systems (IBC and rotating cabin) resulted in time savings per loading cycle. The usage of IBC resulted in a mean decrease of TCL of 1.9 seconds (IBC: on, TCL = 18.6 ± 0.0803 sec.; off, TCL = 20.5 ± 0.0803 sec.). With RC activated, TCL was reduced by 0.9 seconds (Rotation: on, TCL = 19.1 ± 0.0803; off, TCL = 20.0 ± 0.0803).

A significant interaction could be observed between the factors IBC and RC (Supplementary information A1). This resulted in specific distributions of time consumption per loading cycle (**Figure 11**). Lowest TCL was observed when the machine was operated with IBC and RC activated, averaging 17.8 ± 0.114 sec per loading cycle. With IBC activated and RC deactivated (T.F, **Figure 11**), TCL was greater by 1.7 seconds. Significantly higher values of TCL were observed when the crane movement was not supported by IBC, with 20.4 ± 0.114 sec and 20.6 ± 0.114 sec when RC was activated and deactivated, respectively. An influence of RC on TCL could not be confirmed when IBC was deactivated during loading.

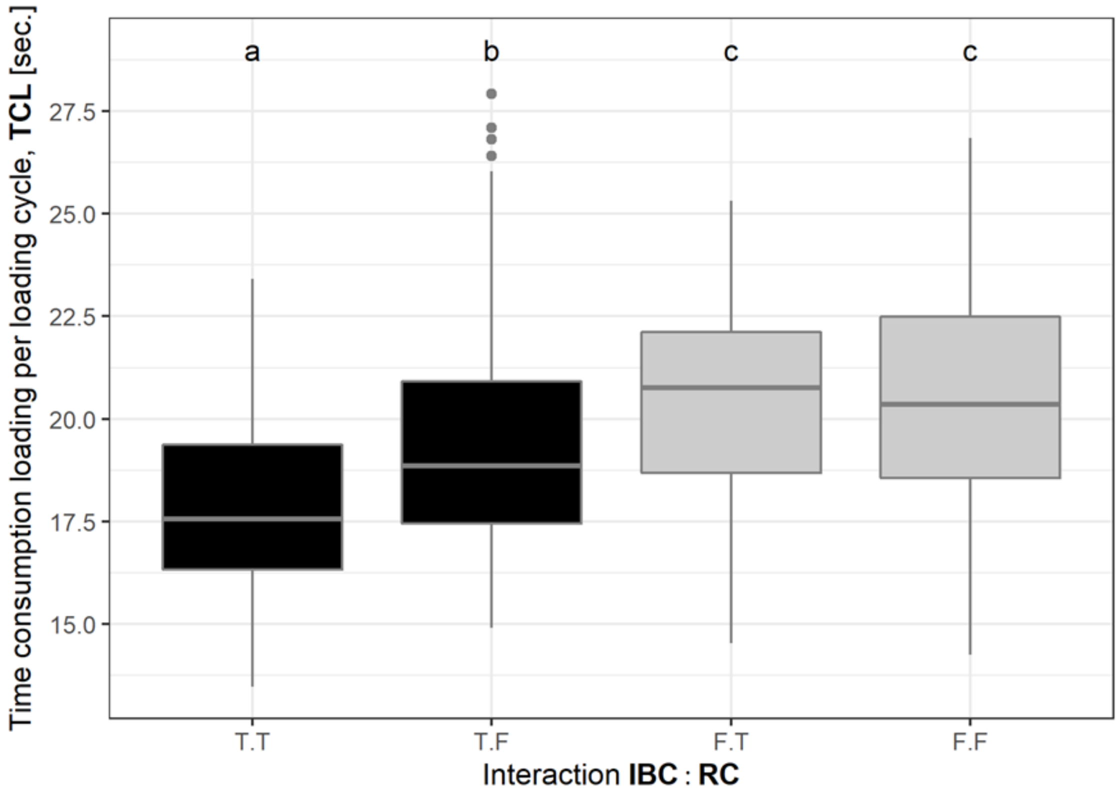

Figure 11: *Time consumption per loading cycle (TCL) of a John Deere Forwarder 1210 G. The 'interaction' (´T´=true, on; ´F´=false, off) refers to the use of the assistance systems IBC (black fill) and RC (grey fill). Small caps indicate significant differences.*

3.4.3.2 Interactions between variants and loading conditions

The differences in TCL between the combination of variants (i.e. IBC:RC) were reflected on the levels of loading distance and loading angle. The overall difference in TCL caused by the utilization of IBC was 1.9 seconds. The analysis showed that the effect of IBC on time consumption per loading cycle was more profound in loading distances between 5.5 m and 8.5 m, as compared to the short or long loading distances of 4.0 and 10.0 m (**Figure 12, A**). At a loading distance of 10 m, differences between TCL per variant were low, with 0.9 sec (**Figure 12, A**). Across the tested loading angles, IBC was able to uniformly reduce TCL (**Figure 12, B**). Contradicting patterns occurred within the variant RC (**Figure 12, C and D**). When a rotation of the cabin was activated, TCL was reduced by 0.9 sec. This value was driven through differences occurring in short and long loading distances. When loading was done at 10 m and RC was activated, TCL (time consumption per loading cycle) decreased by 2.1 sec (**Figure 12, C**), compared to the fixed cabin. Differences in TCL caused by RC generally decreased with increasing loading angle, as shown in **Figure 12 D**.

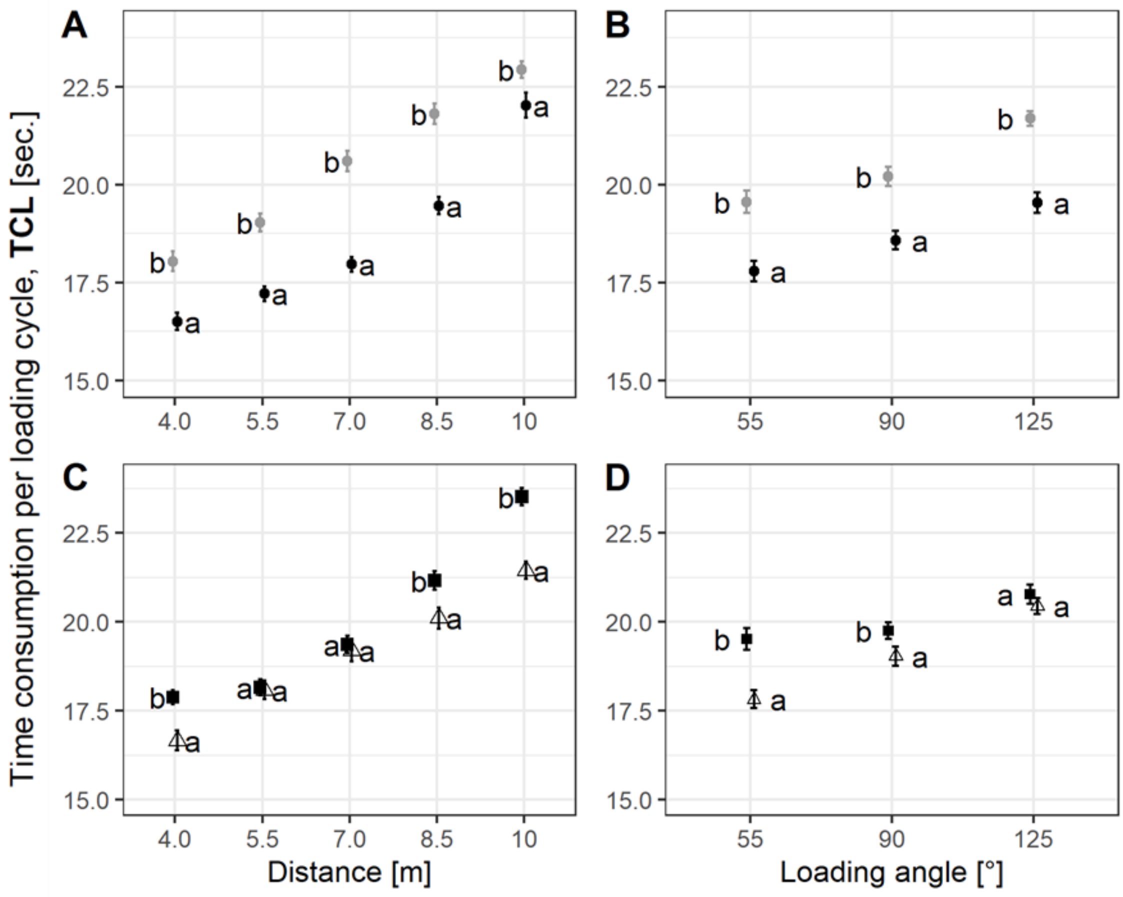

Figure 12: *TCL at different loading angles (n=50) and loading distances (n=30). IBC was either activated (black points) or deactivated (grey points) (A, B). RC was either activated (triangles), or deactivated (squares) (C, D) [600 loading cycles in total].*

3.4.3.3 Time consumption per test variant

Tukey´s HSD post-hoc test was used to identify settings resulting in significantly higher values of TCL in relation to the reference setting, i.e. the setting with the lowest TCL. **Figure 13** illustrates that the lowest mean TCL was observed when loading was done from the shortest distance and smallest angle, and with both IBC and RC activated. Within this combination of activated systems, several settings of loading distance and loading angle resulted in similar loading efficiency. In general, short loading distance and small loading angles led to lower TCL. Without support of IBC, increases of TCL ranged from between +7% and +66% compared to the reference setting (**Figure 13**), with the highest increases occurring at longer loading distances. During loading with IBC activated and RC deactivated, relatively low values of TCL occurred at short loading distances and at a loading angle of 55°, yet high values occurred at the longest loading distance resulting in a maximum increase in TCL of up to +75%.

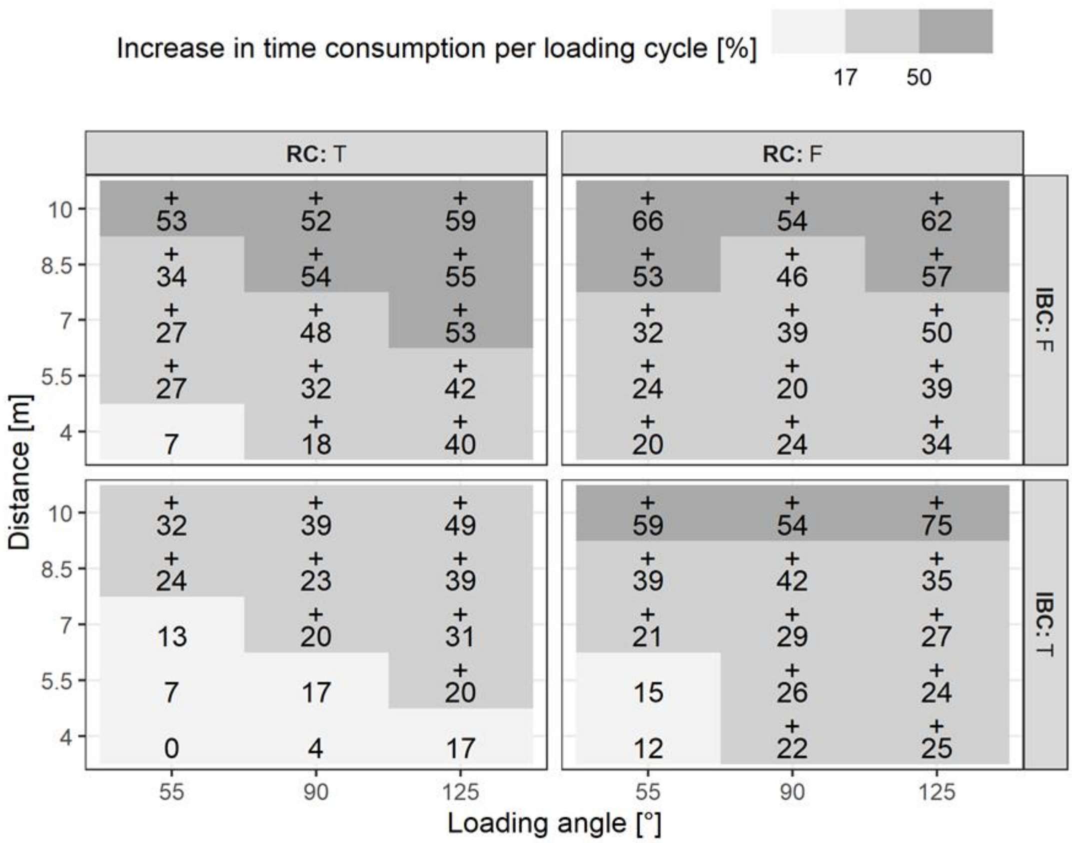

Figure 13: Relative increase in TCL related to the reference setting (14.6 ± 0.935 sec.), using IBC and/or RC (´T´=true; ´F´=false). "+" indicates significant differences according to a Tukey HSD post-hoc test.

3.4.4 Discussion

3.4.4.1 Limitations of the study setup

Overall, the study setup with the possibility to observe standardized loading sequences was suitable to highlight the effect of IBC and RC on time consumption of forwarder loading cycles. Since the loading element occupies nearly 50% of the total extraction time in forwarder work (Ghaffarian et al. 2007), the results may be of importance for practitioners. The isolation of the loading work element allowed for clear measurement of the influence of the chosen operator assistance systems on TCL of forwarders.

The study design was set up to avoid bias caused by terrain- and stand-specific conditions. However, the stationary loading setup was not able to show how e.g. obstacles or terrain related aspects could affect the ability of operator assistance systems to reduce TCL. Other studies revealed that especially boom-tip control systems, can save up to 5.2% of productive machine time in forwarding operations (Manner et al. 2019). Results of the present study revealed 10% time savings for the usage of IBC. The potential impact of IBC in combination with RC (14% time savings compared to the reference setting) is likely to be less profound in practice, as this study only took the loading element into account. This corresponds to the results of Manner et al. (2019) in which time savings less than the results of this study were found. Studies revealed that the use of RC is able to simplify the orientation of forest machine operators in forest stands (Paakkunainen 2015).

Loading distances were adapted to the maximum crane reach. In practice, the positioning of the machine is crucial in loading efficiency (Holzfeind et al. 2018), but also strongly depends on stand- and site-specific characteristics (Proto 2018). Therefore, the study design could only provide limited insight into the influence of operator assistance systems on TCL through the tested loading distances and angles, as the full variety of potential machine surroundings could not be displayed.

The gripping position at the log was pre-defined and marked using spray paint. In practice, machine operators tend to grip the logs slightly offset from the middle to facilitate placement in the load space. Video analysis of the loading cycles showed that this led to few corrections of the gripping position, due to the predefinition of the gripping point, which also increased loading time consumption. Furthermore, no statement can be made on the extent to which the use of both tested systems could influence TCL when using logs longer than 3 m.

Due to limited time, it was not possible to consider loading from both sides of the forwarder. Studies from psychology show that machines are operated according to the individual preferences of their operators (Olson and Sarter 2009). It can be assumed that forest machine operators also have individual preferences that could influence the productivity per loading side.

Due to time and financial constraints, it was decided to work with only one forest machine operator. Therefore, it was important to recruit an experienced operator in order to avoid any bias in observations due to insufficient experience. Homogeneity of variance of the test settings allows for comparison of the sub-samples. The increasing levels in productivity are similar to those measured by Manner et al. (2019). Therefore, it can be assumed that in this study, the effect of operator experience was minimized and that the observed patterns are transferable to other operators, at least to some extent. It was not the objective of this study to conduct an operator comparison, but to analyze standardized loading cycles under the influence of activation or deactivation of IBC and RC, in as detailed a manner as possible. Therefore, it is important to refrain from generalizing the results, as productivity differences between machine operators can be very large (Ovaskainen et al. 2004).

3.4.4.2 Ability of IBC and RC to reduce time consumption per loading cycle

Results showed that TCL (time consumption per loading cycle) varied depending on the loading angle and loading distance, but according to the test variant applied. TCL ranged from between a minimum of 14.6 ± 0.935 sec, observed when loading at a distance of 4 m and under a loading angle of 55 °, with IBC and RC activated, to a maximum of 22.3 ± 1.477 sec.

In a previous study on the loading element itself, the authors did not find a significant difference in TCL between short and long loading distances from the machine, with the relationship between TCL and loading distance behaving non-linearly, with the lowest TCL at medium distances of 4 – 5 m (Hartsch et al. 2022). The results of the present study revealed an increased TCL with increased loading distance

The low variance in TCL could indicate that the machine operator had a high level of experience. In this context, it is important to mention that IBC has a different effect on experienced and beginner machine operators (Manner et al. 2017).

Taking a closer look at the test variants applied, results revealed that the use of the rotating cabin alone had no significant influence on TCL. The situation was different when the RC was deactivated and IBC was activated – TCL was significantly reduced. And when IBC and RC were both activated, TCL was further reduced to 17.8 seconds per loading cycle, which could be related to the generally improved work environment.

It is possible that due to the high level of experience of the machine operator, the potential benefit for productivity of this assistance system was not fully recognizable. Although manufacturers also advertise increased productivity with RC (John Deere 2022 a), this could not be confirmed in the present study, at least with regard to the loading work element. Perhaps a more likely benefit of RC lies in improved operator ergonomics. A positive influence of RC on the posture or movement of the upper body is very likely. Rapid upper limb assessment (RULA) could be an adequate method to investigate strains of the upper musculoskeletal system (Cremasco et al. 2019).

When IBC was activated, TCL was reduced from 20.6 ± 0.114 sec (both systems deactivated) to 18.6 ± 0.0803 sec. It can be assumed that in real-world scenarios the effect of IBC on the whole forwarding cycle would be less profound, since the results of the present study only consider the loading work element. This is also confirmed by other studies (Manner et al. 2019). Machine operators also reported that cognitive load is greatly reduced when using IBC (Bläsing and Bornewasser 2021). Other studies showed that IBC is not only suitable for reducing TCL, but also to reduce damage to the machine caused by crane work (Zemanek and Filo 2022).

A further reduction of TCL to 17.8 ± 0.114 sec was possible, when in addition to IBC, RC was activated. Although a professional machine operator was tested and therefore a low level of variance in time consumption during loading was assumed, TCL could be strongly reduced, depending on the setting applied. It is possible that by using IBC and RC together, the machine operator was able to focus more on the execution of crane work. Based on the results, visibility of the logs could also be crucial in reducing TCL. With RC activated, the field of view was automatically centered to the work area, allowing the operator to focus more on the loading element itself.

In general, the use of IBC and RC had a considerable influence on TCL, depending on the setting applied and interactions between IBC and RC. Apparent synergistic effects between the use of RC and IBC together should also be mentioned here, which may represent a kind of optimum variant based on the results. TCL could be reduced from 20.6 ± 0.114 sec (both systems deactivated) to 17.8 ± 0.114 sec (both systems activated).

3.4.4.3 Interactions between variants and loading conditions

Results revealed that when IBC was activated, TCL could be significantly reduced. However, this effect was strongest between 5.5 and 8.5 m loading distance, compared to loading from a close (4 m) or a far (10 m) distance. TCL could be reduced for all tested loading angles with IBC activated, with the potential for maximum time savings per loading cycle being highest at 125° loading angle.

When loading in the 125° angle, the operator needed to adjust his body’s posture in the cabin to be able to observe the grapple. Due to the change in posture, it is conceivable that the simplified coordination stemming from the help of the IBC system, enabled more purposeful crane movements and thus had a positive influence on loading efficiency. Manner et al. (2017) also reported easier crane operation by using IBC.

For short (4 m) and longer (10 m) loading distances, RC seemed to have a positive effect on time consumption per loading cycle. Taking loading angle into account, a reduction in TCL, with rotating cab activated, occurred at the 55 ° loading angle. However, loading positions of the other angles (55° and

90°) were slightly negatively affected by RC. This could be related to the visibility of the logs. The forest machine operator reported that in some loading positions, the log was briefly hidden from the machine operator's view due to the design of the cabin. Video recordings from the machine operator's point of view for additional in-depth analyses could support this observation.

In general, the use of IBC and RC lead to interactions at certain loading distances and loading angles. However, the effect of the tested systems varied depending on the loading setting. In a nutshell, a reduction in TCL was seen with IBC under all loading distances and angles, but especially at medium loading distances (5.5 – 8.5 m) and "unproductive" loading angles (125 °). RC showed advantages especially in the 55 ° loading angle.

3.4.4.4 Time consumption per test variant

When IBC was deactivated, TCL increased between +7 and +66% compared to the reference variant, depending on the loading angle and distance. Although the maximum increase occurred with IBC activated (+75% compared to the reference variant), it can be stated that the overall increase in time consumption with larger loading angles and distances is lower when using IBC. Results showed that IBC could be the decisive factor for a possible reduction in the time requirement. However, significant increases in TCL (up to +17%) also occurred when IBC was activated and the RC was deactivated. The use of IBC seemed to lead to improved focus on the work task. By eliminating the extension joystick function, the forest machine operator can concentrate more on the loading process. Studies revealed that cognitive demands and task complexity can affect human performance and workload (Layer et al. 2009, Bläsing and Bornewasser 2021).

Compared to the reference setting, the smallest increase in TCL was observed in the 55 ° loading angle. Short loading distances also seemed to be advantageous. The results confirm the findings by a previous study (Hartsch et al. 2022), where shorter loading distances as well as small loading angles were highlighted as optimal loading settings.

It can be concluded that based on the results of this study, it is less the RC that appears to be characteristic for an improvement in loading productivity, but rather the use of IBC. In this context, the effect of IBC seems to be stronger at different loading angles and distances (see 4.3). However, the most productive loading areas are quite close to the machine. The study has demonstrated the importance of the preliminary work of the harvester for the subsequent forwarder, as for example

Manner et al. (2013) and Väätäinen et al. (2006) have shown as well. Especially in thinnings, the demand on log placement increases. If these are positioned close to the machine operating trail, the work is made easier for the forwarder operator due to reduced loading distances resulting in shorter loading cycles.

Overall, future research should aim to investigate more factors that affect forwarder productivity. In forest engineering, it is fundamentally difficult to create laboratory conditions. The goal of the present study was to create as controlled loading conditions as possible to be able to investigate how operator assistance systems could impact time consumption of forwarder loading cycles. However, since the loading element alone is not sufficient for a comprehensive assessment of a forwarder´s productivity, future studies could include more complex aspects affecting forwarder productivity, such as obstacles in the loading area or further operator comparisons. The study does not claim to be exhaustive, but it does give some indications to how further studies could be structured. In addition to already existing studies, the effectiveness of IBC during training of machine operators should be further examined, as well as technical advancements of the systems and their effect on the productivity of the loading process.

3.4.5 Conclusions

Summarizing, the results have shown three key findings:

1. In total, the use of IBC was able to significantly reduce TCL. In combination with IBC, the use of RC lead to a further reduction in TCL.

2. When using IBC, TCL was reduced over all tested loading distances and angles. This effect became more pronounced when IBC was activated in medium loading distances (5.5 – 8.5 m) and in the 125 ° loading angle. The use of RC reduced TCL, especially at short (4 m) and long (10 m) loading distances, as well as in the 55 ° loading angle.

3. Productive loading “areas”, showing the highest potential for time savings during loading cycles were found to consist of shorter loading distances and small loading angles, which can be supported extensively by using operator assistance systems. This shows the importance of appropriate positioning of the forwarder before loading.

The methods applied as well as the different variants and settings are suitable for performing an in-depth-analysis of the loading work element. However, the transferability to real-world scenarios is limited, since other work elements and factors influence TCL.

Due to the importance of highly mechanized timber harvesting systems in world forestry, a detailed analysis of further performance determining factors is suggested. The analysis of factors influencing forwarder productivity, differentiated by work elements, can contribute to increased productivity of forest machines and therefore a reduction of harvesting costs. Although softwood stands are deeply affected by drought and bark beetle infestations in central Europe, highly mechanized harvesting systems will continue to be state-of-the-art technology, as many areas are reforested with other coniferous species, such as larch or Douglas fir. Even in younger hardwood stands, harvesters and forwarders are increasingly used.

The study cannot fully represent real-world conditions since other performance determining factors and work elements were not considered. However, the goal of this study was to analyze the influence of selected operator assistance systems on the loading work element itself, in as much detail as possible. Since the loading element is one of the most important in forwarding operations, the results can contribute to a better understanding of performance determining factors in highly mechanized harvesting systems and provide a basis for further investigations.

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Conflicts of Interest

The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results.

Appendix A1

Table 11: *Analysis of Variance Table.*

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Distance	4	2,049.76	512.44	265.11	7.21e-126
IBC	1	513.10	513.10	265.45	7.79e-49
Angle	2	383.94	191.97	99.31	1.87e-37
RC	1	125.46	125.46	64.91	5.06e-15
Distance:IBC	4	55.57	13.89	7.19	1.21e-05
Distance:Angle	8	64.63	8.08	4.18	7.20e-05
IBC:Angle	2	7.46	3.73	1.93	1.46e-01
Distance:RC	4	81.88	20.47	10.59	2.88e-08
IBC:RC	1	77.32	77.32	40.00	5.33e-10
Angle:RC	2	49.42	24.71	12.78	3.76e-06
Distance:IBC:Angle	8	64.29	8.04	4.16	7.72e-05
Distance:IBC:RC	4	12.63	3.16	1.63	1.64e-01
Distance:Angle:RC	8	31.71	3.96	2.05	3.89e-02
IBC:Angle:RC	2	25.08	12.54	6.49	1.64e-03
Distance:IBC:Angle:RC	8	33.35	4.17	2.16	2.93e-02
Residuals	540	1,043.80	1.93	NA	NA

4. Summary of Publications

4.1 Paper I: Positive and Negative Work Practices of Forest Machine Operators: Interviews and Literature Analysis

Citation: Hartsch, F.; Dreger, F.A.; Englund, M.; Hoffart, E.; Rinkenauer, G.; Wagner, T.; Jaeger, D.: Positive and Negative Work Practices of Forest Machine Operators: Interviews and Literature Analysis. *Forests* **2022**, *13*, 2153. https://doi.org/10.3390/f13122153

Summary: Fully mechanized harvesting systems enjoy great economic importance in forestry worldwide. Operating these machines requires lengthy training. Even experienced operators face high cognitive demands and show differences in productivity. Work carried out by forest machines can be divided into different work elements. Work methods as part of these work elements are defined as standardized ways to conduct operations. However, work practices are work methods under a subjective influence of machine operators. Still, it is unclear how these work practices affect performance of fully mechanized harvesting systems. Therefore, **Paper I** aimed to define positive and negative forest machine operator work practices, which affect system productivity, machine wear, and mental strain.

To achieve the objectives of the study, a two-fold research approach was chosen, which consisted of expert interviews and a literature analysis. A total of 15 semi-structured interviews with forest operator instructors was conducted in Germany, Sweden and Norway. Interviews were recorded, transcribed, paraphrased, and anonymized. The interview analysis was conducted using the software MAXQDA v. 12.3.5. When analyzing the transcripts within a coding system, phrases on the study objectives were selected by type and then related to predefined categories. In a second step, a literature analysis on positive and negative work practices of forest machine operators was conducted. The PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used for filtering the literature retrieved. Several scientific databases such as Scopus, PsychInfo, GreenFile, and Web of Science were examined. Additionally, literature recommendations from senior scientists were integrated. After searching the databases, 2480 journal articles were included for screening. Final analysis inclusion criteria were defined. Finally, 16 articles were used for data extraction.

Results of the interview analysis showed that for both harvesters and forwarders excessive use of crane reach, too high or too low crane speed, bad positioning and a low grade of maintenance can be described as some of the work practices which negatively affect productivity, work satisfaction and machine wear. The results of the literature analysis revealed that work practices were only sparsely covered in recent studies. A knowledge gap regarding work practices could be identified. In general, positive work practices can be described as the awareness about effective boom working ranges, appropriate machine (re)positioning and assortment pile sizes.

The results have shown that work practices are well known by operator instructors. The efficiency of harvester and forwarder work can be increased when being aware of the influence of forest machine operator work practices on several aspects of the work cycle. The results of this study can provide insight into the extensive list of positive and negative work practices and can therefore be used in forest machine operator training. Additionally, the results can serve as a basis for further scientific studies.

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

Citation: Hartsch, F.; Schönauer, M.; Breinig, L.; Jaeger, D. Influence of Loading Distance, Loading Angle and Log Orientation on Time Consumption of Forwarder Loading Cycles: A Pilot Case Study. *Forests* **2022**, *13*, 384. https://doi.org/10.3390/ f13030384

Summary: As **Paper I** showed, forest machine operator work practices also cover performance in crane work. Crane work is performed by both harvester and forwarder operators. Within these fully mechanized CTL (cut-to-length) work systems, productivity of the forwarder is related to various aspects, such as site- and stand-specific characteristics, technical parameters, organizational aspects, and operator-related performance. When operating a forwarder on machine operating trails, depending on the machine's positioning and the precursory harvester work, different loading distances, loading angles, and log orientation angles arise. As loading occupies nearly 50% of the forwarder cycle time (Ghaffarian et al. 2007), deeper insight into this work element was required. A closer look at this work element promises optimization potential for the collaboration between harvester and forwarder. Therefore, the goal of **Paper II** was to discover the influence of loading angle, loading distance, and log orientation angle on time consumption of forwarder loading cycles.

The study was conducted using a stationary Rottne F10 simulator, which consists of an operator cabin, a load space, and a crane. Compared to "field machines", a wheeled undercarriage is missing, and the crane hydraulics are powered by an electric motor. All other components are the same. The goal of the methodology was to carry out standardized and repeatable loading sequences. Therefore, five different loading distances from the crane pillar (3 m, 4 m, 5 m, 6 m, 7 m) over three different loading angles (45°, 90°, 135°) relative to the machine axis were set up. For each of these 15 loading positions, the log orientation angle was varied (45°, 90° and 135° to the machine axis). Every setting was tested in ten repetitions, so that a total of 450 loading cycles could be measured. To attain comparable results, an experienced operator was crucial to the study.

The results of the study revealed a significant influence of all three tested variables on time consumption per loading cycle. Loading at a close and a far distance from the machine (3 m and 7 m) showed increased time consumption per loading cycle. Additionally, time consumption per loading cycle increased with increasing loading angle and log orientation angle. Results showed that loading at a 90° angle to the machine axis, at a distance of 4 – 5 m from the machine, and log orientation angles of 45 and 90°, was beneficial for loading time consumption. On the opposite, a loading angle of 135°

to the machine axis, close and far distance from the machine (3 m and 7 m), was unbeneficial for loading efficiency.

In general, the results could only provide an insight into work practices of forwarder operators. The results support the findings of **Paper I** and can serve as an insight into “best practices” not only of forwarder operators, but also harvester operators. Among other factors, not only is the positioning of the forwarder decisive for system efficiency, but also the placement of the logs by the harvester operator beforehand. Assortments, placed as near to the machine operating trail as possible (to reach beneficial loading distances for the forwarder), could result in an optimal loading range for the forwarder and thus increase system productivity. The data from **Paper II** are not fully generalizable. However, practitioners confirmed that the same “beneficial” work practices investigated are preferred by machine operators as “best practices”.

4.3 Paper III: Effects of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study

Citation: Hartsch, F.; Schönauer, M.; Pohle, C.; Breinig, L.; Wagner, T.; Jaeger, D. (2023): Effects of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study. *Croatian Journal of Forest Engineering* (article accepted, expected publication in the end of 2023).

Summary: **Paper I** and **Paper II** showed the importance of forest machine operator work practices in fully mechanized timber harvesting systems and gave insights into potential "Best Practice" operations to further optimize workflow between harvesters and forwarders. Over the past decades, operator assistance has become increasingly important. Operator assistance can be related to indirect support, such as routing and mapping software, but also to direct assistance during the operation of a forest machine, such as rotating cabins and boom-tip controls. Since operator assistance has gained importance in machine operation, the goal of **Paper III** was to understand the influence of boom-tip control and rotating cabins on time consumption per loading cycle of a forwarder.

Therefore, a study setup compared to **Paper II** was chosen with slight differences. The loading distances were adapted to the crane reach of a forwarder John Deere 1210 G (4 m, 5.5 m, 7 m, 8.5 m, 10 m from the crane pillar) and then over three loading angles (55°, 90° and 125° in relation to the machine axis). These 15 loading positions were then repeated in four variants, related to the usage of "Intelligent Boom Control" ("IBC", John Deere 2022b) and a rotating cabin: IBC deactivated, rotating cabin deactivated (Variant I); IBC deactivated, rotating cabin activated (Variant II); IBC activated, rotating cabin deactivated (Variant III); IBC activated, rotating cabin activated (Variant IV). All variants were tested with 10 repetitions each, resulting in a total of 600 loading cycles.

The results revealed that the rotating cabin alone had no significant influence on time consumption per loading cycle. However, the use of IBC resulted in a significant loading time reduction of around 10%, compared to the reference setting (both systems deactivated). The use of IBC and rotating cabin in combination seemed to result in positive synergies. The mean time consumption per loading cycle could be reduced by approximately 14%. Loading at smaller angles to the machine axis (55°), from medium loading distances (4 – 5 m), using IBC and a rotating cabin seemed to be the most efficient way of loading. When both systems were deactivated and loading was performed at increased loading distances and loading angles, time consumption increased by up to 60% compared to the reference variant.

Since the loading element of the forwarder represents around 50% (Ghaffarian et al. 2007) of the whole cycle time, loading in combination with varying work practices is suggested as the subject of further studies. The results of this study have no general validity, but are supported by the results of other studies and the personal experience of forest machine operators. The study results do not allow for an assessment of the effects of operator assistance systems on the mental strain of operators. However, since the demand on forest machine operators and forest operations in general is increasing, operator assistance could play a decisive role in job satisfaction of operators and cost-effectiveness of fully mechanized harvesting systems.

5. General Discussion

5.1 Influence of forest machine operator work practices on system performance

The results of **Paper I** showed that work practices of forest machine operators could be defined by conducting a literature analysis and expert interviews. Literature analysis showed that fully mechanized harvesting systems are studied well, in general. However, analyses of forest machine operator work practices are only sparsely covered in scientific literature. The 15 expert interviews conducted, resulted in a list of positive and negative work practices and expert recommendations for harvester and forwarder work. Whether a work practice was deemed “beneficial” or not seemed to depend mostly on the productivity of the operator (m^3 per hour), and the reduction of machine wear and fuel consumption related to the carbon footprint of timber harvesting operations (Hartsch et al. 2022 b). Based on the results, beneficial work practices are related to appropriate positioning (based on the crane reach), adjusted driving speed, appropriate crane work (using of telescope), felling and processing without timber damages, and piling (separation of assortments, piles adapted to grapple size of forwarder). If operators do not perform like this, work practices can be considered as negative (chapter 3.2).

When planning the study, the use of surveys over interviews was discussed. In general, surveys would have given more insight into opinions and convictions of the forest machine operator population. Additionally, a higher degree of standardization in surveys leads to more statistically profound information (Jäschke and Uhrig 2022). However, as no reference can define the number of forest machine operators in Germany, and accessibility to them as survey respondents is limited, expert interviews were rather decided on. To gain insight into operator work practices, forest machine operator instructors were interviewed. Their extensive knowledge and experience and high number of trained forest machine operators proved valuable to the study. Demographic data in **Paper I** show that the number of trained operators ranged from 40 to 300 (Hartsch et al. 2022 b). Operator instructors frequently operate forest machines themselves. Therefore, it can be assumed that arguments given by the instructors could be considered “relevant” for practice.

After analyzing the interviews, a list of work practices was compiled, with some of these aspects named by all instructors over the three participating countries. Some arguments were only mentioned by Scandinavian or German instructors, respectively. These were mostly related to the forest management practices relevant to the specific country. In Scandinavia, clear felling by applying the CTL (Cut-to-length) method is a common technique to harvest large-scale softwood areas. According to the Bundeswaldgesetz (BWaldG), clearcuts are not fundamentally prohibited in Germany. However, different state laws prohibit it by relation to the tree volume remaining in the stand (§ 10 LWaldG), or at least require a notification of planned operations, depending on the intensity (§ 12 NWaldG). In Germany, clearcutting is performed in a rather limited manner (Setzer 2018), except for so-called calamity stands resulting from catastrophic storm and drought events over the last years. The work practices mentioned were classified by type and referred to categories within the types (Harvester: positioning and reaching for trees, felling, crane settings, crane use, other; Forwarder: Crane settings, crane skill, loading, unloading; Value: value; Teamwork: teamwork and psychology) (Hartsch et al. 2022 b). Without clustering the interview responses, it would not have been possible to compile the results. After transcription and anonymization of the interviews, it became apparent that an extensive amount of information could be extracted from the interviews. This was probably related to the semi-structured nature of the interviews. The interviewees were given sufficient time to answer the questions. The explorative focus of the interviews highlighted many ideas for further research focusing on forest machine operator work practices. It can be assumed that not all, but many work practices could negatively affect several aspects within fully mechanized timber harvesting (**Paper I**). Therefore, the results can contribute to further analyzes of working behavior. A weakness of the interviews is that individual work practices could only be roughly classified by their impact on productivity, fuel consumption, or machine wear. **Paper II** can deliver deeper insight by using laboratory conditions to analyze work practices quantitatively. The investigation of work practices is related to time and effort, and therefore financial constraints. The analysis of performance determining aspects within fully mechanized harvesting systems is far from complete. Supporting this, the results of **Paper I** can generate ideas for further research, e.g. investigations on the effects of these work practices on productivity. Work practices of forest machine operators are mostly related to machine positioning, crane work and work organization. This is supported by literature, which also considers work practices e.g., for log bunching, as decisive for forwarding efficiency (Väätäinen et al. 2006). Related to positioning, it seems to be essential to keep the distance to the trees to be harvested or the logs to be loaded quite short, which is also underlined by the results of **Paper II**. Regarding crane work, literature only sparsely covers beneficial ways to operate cranes. Within the results of **Paper I**, a list of beneficial and non-beneficial work practices is given, which can be applied by forest machine operators to further develop their skills. Work organization is also mentioned in literature as a decisive factor for efficiency of fully mechanized harvesting systems (Persson 2013). The results showed that emphasis was placed on value recovery and teamwork aspects by the interviewees. This is supported by literature, as teamwork between harvester and forwarder is considered one of the most important aspects in fully mechanized timber harvesting (Persson 2013).

The literature reviewed resulted in a concise list of forest machine operator work practices (Hartsch et al. 2022 b). The results focused on beneficial loading conditions (Hartsch et al. 2022 a), an optimized driving speed (Vasiliauskas et al. 2021), instructions on reduced tree damage (Bembenek et al. 2020), workload (Spinelli et al. 2020), beneficial thinning techniques (Ovaskainen et al. 2011), driving instructions (Andersson and Eliasson 2004), grappling instructions (Manner et al. 2020), and recommendations for processing, bucking and loading (Ovaskainen et al. 2004, Väätäinen et al. 2006). This research shows that forest machine operator work practices and related cognitive aspects are indeed the subject of current research (Dreger et al. 2023). However, it can be noted that these work practices often are not considered as such. Research should focus more on the classification of work practices to further adapt this list of work practices. More clarity about the influence of work practices on work systems is intended, since **Paper I** identified that literature often does not differ between work methods and work practices (Hartsch et al. 2022 b), even if the difference is clear, according to REFA (1998). The extent of forest machine operator training seems to be based on the experience of the operator instructors and the quality of the internal education documents. A scientific view on working behavior, as applied in **Paper I**, could support understanding of operator needs and support the adaption of operator training accordingly. It is essential to share the results with practitioners to ensure that these results find their way to the machine operators. In general, a well-founded training on machines is decisive to work productively, conserve stand and soil, and work in an environmentally-conscious manner (Persson 2013).

In general, according to REFA institute, work practices can be defined as individual-subjective ways to perform a work method, (REFA 1998). The results showed that analysis of scientific literature alone cannot sufficiently quantify work practices, since these are performed by the machine operators themselves and the exchange between science and practice is often limited. Positive and negative work practices arise both in operating harvesters and forwarders. A work practice can be described as positive, if it results in increased productivity, reduced machine wear, reduced carbon dioxide emissions, increased value creation, and greater job satisfaction. The compilation of work practices can be seen in **Paper I**.

5.2 Optimization potentials of loading distance, loading angle and log orientation angle in fully mechanized harvesting systems

Results of **Paper II** revealed that all tested variables showed a significant influence on time consumption per loading cycle of a forwarder. Data analysis showed that “optimal” loading conditions and therefore, “best practices” of forest machine operators could be quantified. Loading at a near (3 m) and far (7 m) distance from the machine led to significant higher time consumption per loading cycle, compared to more “beneficial” loading distances (4 m, 5 m, 6 m). Results also showed that time consumption per loading cycle seems to be positively correlated to the loading angle applied. Based on the data, the most inefficient way to load logs seems to be at an angle of 135°, relative to the machine axis. Log orientation angles also affect time consumption per loading cycle and therefore the efficiency of fully mechanized harvesting systems. Based on the results, an increasing log orientation related to the machine axis and the machine operating trail, leads to increased time consumption per loading cycle. A log orientation angle of 45° relative to the machine axis achieved the lowest cycle times (Hartsch et al. 2022 a).

First and foremost, the correlation between loading distance and time consumption per loading cycle does not seem to be linear. Loading at short distances is related to higher time consumption, due to poor visibility of the logs and slower handling of the crane to avoid contact (damages) to the machine. Higher time consumption when loading at a further distance from the machine (7 m) mostly represents longer crane paths and counter-movements to reduce crane-tip oscillation. Good visibility of the logs and “better” loading conditions (4 – 6 m loading distance from crane pillar) resulted in the lowest time consumption per loading cycle. This is also supported by the results of **Paper III** and initial studies with different operators. Studies reveal that positioning of forest machines could be a decisive factor for the efficiency of the entire fully mechanized harvesting system, including both harvesters and forwarders (Väätäinen et al. 2006, Hartsch et al. 2022 a). The results support a more holistic view on efficiency-determining aspects, as loading or grapping distances can be directly influenced by both forwarder and harvester operators. In practice, logs are placed at the edge of the machine operating trail by the harvester. However, if the harvester operator places logs too far from the edge of the trail, loading distances increase, which could then potentially negatively affect system efficiency. In literature a distance of 1-1.5 m from stack ends to wheels is given (Persson 2012), which should result (depending on the length of the logs) in beneficial loading distances related to the results of Paper II and III. Therefore, the data can contribute to a better understanding and the definition of “best practices” within mechanized harvesting. Based on the results of **Paper II**, harvester operators should deposit logs directly at the edge of the machine operating trail to keep loading distance manageable. Other studies reveal that the type of log bunching along the machine operating trail can also affect forwarder efficiency (Väätäinen et al. 2006). That emphasizes that the precursory harvester work and the forwarder's loading position influences the overall productivity of fully mechanized harvesting systems. Literature supports the focus on teamwork between system compartments of a fully mechanized harvesting system (Persson 2013). Operators become aware of each other´s strengths and weaknesses and work to adapt accordingly to make an efficient harvesting team (Persson 2013). Research shows that this communication between single stakeholders within the wood supply chain is often lacking (Bodelschwingh 2006). However, the results presented in this thesis only serve as a snapshot of a bigger picture, since one only operator was tested due to time and financial constraints. Other operators would probably not have shown the same pattern of time consumption. Most likely, the patterns would have been similar, which is supported by several unpublished loading studies. The difference in loading performance between beginner and experienced operators remains unclear. Scientific literature revealed an influence of operator behavior and experience on performance, but this does not always represent a linear relationship (Purfürst 2009). The results presented in **Paper II** and **III** are also relevant to a specific machine type. In general, loading at an angle of 45° and 90° (relative to the machine axis) seems to be beneficial compared to loading at an angle of 135°. However, efficient loading at a 45° angle seems to be unknown, as beneficial loading conditions are only sparsely covered in literature (e.g. Persson 2013). The results are related to the performance of one professional machine operator and therefore only serve as insight into performance determining loading conditions. Relating the results to practical harvesting and forwarding conditions, conclusions on best practices of both harvester and forwarder operators can be made. The loading angle is mostly affected by the positioning of the forwarder, but also by the harvester work practices, e.g., areas with steep slopes or rocks present difficult loading conditions with few possibilities to position the machine optimally. The results support the narrative that machine positioning has an influence on whole system efficiency. A higher time consumption for the loading process leads to lower productivity (m^3 per hour). Therefore, the results can not only contribute to forest machine operator training, but also towards evaluating work practices of experienced forest machine operators. The results also revealed an influence of log orientation on loading time consumption, which is also a new aspect in efficiency analysis of fully mechanized harvesting systems. The log orientation is determined by the deposition of the logs at the edge of the machine operating trail by the harvester operator and by the direction that the forwarder operator drives the forwarder into the stand on the machine operating trail. In practice, a forwarder operator would not decide on the stand entry direction based on the log orientation, even if it was affecting his productivity. In most situations, especially in areas with higher slope, only one direction exists from which the stand is accessible, and the logs need to be loaded irrespective of their orientation. Log orientation affects time consumption per loading cycle and therefore influences productivity of fully mechanized harvesting and forwarding operations. The log orientation also influences loading of log assortments, e.g., when the harvester operator is performing separation cuts, it would be noticeably better for the forwarder operator, when sawn wood and pulp wood are separated from each other. To achieve this, the harvester operator would only need to slightly adjust the orientation of the aggregate after the sawn wood separation cut to initiate a small angle between different assortments to simplify loading. The effect of ordered and clustered wood piles is also mentioned in literature (Persson 2012). However, based on this study's results, log orientation data are related to the operator tested. Most likely, time consumption per loading cycle is affected by log orientation due to personal preferences of the operator, as no real technical reasons can be used to explain this effect. Other studies show that personal preferences of operators do in fact exist (Olson and Sarter 2000), meaning that this should be explored in more detail in the future. This study could however not display the full variety of loading conditions in practice and therefore only serves as a detailed analysis of single factors that affect loading time consumption. In forest operations, it is difficult to recreate laboratory conditions. Additionally, financial constraints related to machine cost or time constraints often prevent comprehensive and thus lengthy investigations. In general, the results presented here can also be used to further develop "best practices" for forest machine operators. More research on the loading element itself is recommended.

Taking all relevant aspects into account, **Paper II** contributed to the analysis of performance-determining factors within mechanized timber harvesting. All tested variables (loading distance, loading angle and log orientation angle) significantly affected time consumption per loading cycle of a forwarder. Regarding the definition of "best practices", harvester operators should deposit logs directly at the edge of machine operating trails to generate medium ("beneficial") loading distances for the forwarder operator. Additionally, depositing the logs at an angle of 45° or 90° to the trails seems to be more efficient practice. To keep time consumption per loading cycle short, forwarder operators should position the machine close to the wood piles and at a 45° to 90° angle, (Hartsch et al. 2022 a). Therefore, the results presented support the collection of efficiency influencing work practices related to **Paper I**.

5.3 The suitability of operator assistance to increase forwarding efficiency

Operator assistance systems were found to affect the efficiency of fully mechanized timber harvesting systems. The results of **Paper III** showed that under given loading conditions, operator assistance was able to decrease time consumption per loading cycle of a forwarder. The productivity of fully mechanized harvesting systems can benefit from these systems. This is supported by results of recent research (Manner et al. 2017, Manner et al. 2019). The methodology of **Paper II** was adapted and modified to accurately retrieve data on a potential influence of boom-tip control and rotating cabins on time consumption of forwarder loading. Manufacturers advertise the positive effects of both systems on machine and operator performance (John Deere 2023 c, John Deere 2023 d). The data revealed that a rotating cabin alone, does not have a positive impact on loading time consumption. Boom-tip control alone did however show a reduction of time consumption. When both assistance systems were engaged, a greater reduction of time consumption was reported. Conducting holistic investigations of work systems in the context of forest operations often means that single work elements have to be analyzed within long time series data. Under the present methodology, the forwarder loading element and the interaction with operator assistance could be isolated.

Operator assistance will probably soon dominate the mechanized harvesting rationale. Operating forest machines is characterized by changing stand, soil, weather, and organizational aspects, which requires high operator adaptability (Persson 2013). Hence, mental workload is high when operating a forest machine (Gellerstedt 2002). The results of **Paper III** could not show a decreasing mental workload, as this factor was not intended to be tested within the methodology. How effectively operator assistance systems reduce mental strain is partly dependent on the machine operator. However, more research needs to be done to reveal the effect of operator assistance systems on the mental workload of operators.

Although current research is concerned with autonomous forest machinery (Ringdahl 2011), it is very unlikely that completely autonomous forest machinery will be commonplace within the next few years. Therefore, operator assistance will play an even more important role. **Paper III** shows that operator assistance has a significant positive effect on time consumption per loading cycle of forwarders. When considering contractors and machine owners, references suggest that at present many machine owners still seem to work with machines which are not equipped with boom-tip controls or rotating cabins (KWF 2018). Nowadays, integrated boom-tip controls are commonplace for most manufacturers (John Deere 2023 c, Komatsu 2023, Ponsse 2023 b), however rotating cabins are not yet commonplace in mechanized timber harvesting. Naturally, the longer a machine is in operation, the greater the economic benefit of such operator assistance systems could be (Biernath 2023). Even if the performance of harvesters under the usage of both assistance systems was not tested, the results indicate that a positive effect of operator assistance on productivity, machine wear, and mental workload of a harvester operator could also be expected (Hartsch et al. 2022 b). The study did not intend to test the ergonomic effects of both assistance systems on the forest machine operator. Based on unpublished interviews with several forest machine operators, boom-tip control and rotating cabins both could have a positive effect on operator ergonomics. When working with rotating cabins, the operators´ head does not need to be turned, since the cabin follows the grapple (John Deere 2023 e). A RULA assessment (Cremasco et al. 2019), evaluating posture of the upper body during work, could be used to understand the ergonomic advantages of rotating cabins. To assess ergonomic advantages of boom-tip control, eye-tracking systems could potentially give insight into mental strain of operators (Naskrent et al. 2022).

A holistic view of the wood supply chain reveals that the timber production process causes high costs for the landowners. Therefore, forest work science is constantly searching for improvement potential. Operator assistance seems to be one of the most efficient developments in forest technology within the last few years. Contractors and machine owners should consider including operator assistance systems when purchasing new machines. Digitalization in combination with operator assistance, seems to offer great potential for improvement of fully mechanized timber harvesting systems. An example of one such foreseeable integration could see the mapping tools capable of connecting data on the harvested timber volume with position data showing exactly where that timber was harvested. Forwarder operators could then optimize their operations, since differences between timber assortments, related volumes, and empty areas in the operation zone would be clearly discernible (John Deere 2023 a). Another advantage of this could be reduced impact on soil, even if this impact is also related to organizational (planning and number of landing areas) and technical (usage of bogie tracks) aspects (John Deere 2023 f). Furthermore, tools for planning routing is established within timber logistics (Hansson et al. 2022). Data on the position of processed timber volumes has the potential to optimize the entire wood supply chain (Müller et al. 2019). However, data privacy remains a concern of forest machine operators (Ottl et al. 2021).

The results of **Paper III** revealed that both tested assistance systems in combination were able to significantly reduce time consumption per loading cycle for a forwarder. The combination of both systems lead to a significant time reduction of 14% per loading cycle. In field operations, this effect would most likely be less pronounced. However, the findings of **Paper III** are supported by the findings of other studies, which suggest that operator assistance will become one of the most important aspects to improve the economics, ergonomics, and environmentally-friendly use of forest machinery. When considering the entire wood supply chain, it is clear that forest operations play a significant role when assessing the economic, ecological and social impact of modern forest management. Striving towards a sustainable forest economy means that work science related improvements should be implemented to ensure the continuation of efficient, ecological, and socially compatible timber harvesting. Since demand for timber as a sustainable raw material is projected to increase over the next few years (DeSH 2021), timber harvesting and utilization, and therefore sustainable land use should continue to be subject of scientific investigations and, above all, be also supported in terms of forest policy.

6. General Conclusions and Outlook

The results of the studies presented in this thesis have shown that positive and negative forest machine operator work practices could be quantified through means of a literature analysis and by conducting interviews. The effect of work practices still seems to be an underestimated factor when assessing the economic, ecological, and social aspects of fully mechanized harvesting systems. Studies have shown that the forest machine operator affects the entire system's productivity. The present thesis showed that work practices can have a significant influence on time consumption per loading cycle, which could therefore influence machine wear and also the carbon footprint of fully mechanized timber harvesting operations. The results can be used by practitioners and educators to optimize working behavior through informative "Dos and Don'ts" of forest machine operation.

The results also revealed which forwarder loading conditions lead to decreased time consumption. Scenarios with medium loading distances, low loading angles (less than 90° relative to the machine axis), and a low log orientation angle lead to decreasing time demands for loading processes. Time consumption per loading cycle increased when loading from close and far from the machine, at higher loading angles and higher log orientation angles. The results provide indicators for optimized work practices or "Best Practices" of harvester operators. The results revealed that negative work practices of the harvester (depositing logs too far from the machine trail, at unfavorable angles) can negatively affect forwarder productivity, measured by quantifying time consumption per loading cycle. These findings could be used in forest machine operator training.

Operator assistance in fully mechanized harvesting systems, such as rotating cabins or intelligent crane controls, is becoming increasingly important. The results revealed that the combination of both systems could lead to a significant reduction of forwarder loading time, up to 14%. Therefore, the additional economic investment in these systems is justified when considering the improvement in productivity they can deliver. This financial reasoning makes sense for machines in operation for 10.000 hours and more. Since these assistance systems were tested on professional forest machine operators with extensive machine operating experience, it can be assumed that other machine operators would show similar patterns of improved productivity. Results of unpublished studies support this statement.

Forest transform is making progress in Germany. The increased focus on climate resilient forests, with a diversity of tree species and diameter and height structures, will lead to a change in timber harvesting in the coming years. Combined skidders most likely will operate in highly diverse and complex forest stands, especially in hardwood stands of higher diameter classes. However, due to the high efficiency and beneficial occupational safety, fully mechanized harvesting systems will continue to play an important role in forest operations. This is reflected by the increasingly broadened range of applications of such systems. For example, harvesters and forwarders are now working in hardwood thinning operations, which was previously unheard of. Another advantage of fully mechanized harvesting systems is the ability to digitally integrate with neighboring systems, for example, the integrative use of forest machine data in subsequent timber processing steps or chain-of-custody validation (Hartsch et al. 2021). Fully mechanized systems can therefore offer high adaptability and flexibility, making these the preferred systems for stands that have suffered catastrophic storm events where big amounts of calamity timber needs to be removed. The use of data on the harvested production, harvested area, soil trafficability, and fuel consumption will most likely increase in the next few years towards optimization of whole work systems and the wood supply chain. Forest companies and contractors who operate forest machines should be open-minded about the advantages of digitalization to further profit within the forestry sector. Additionally, it is unlikely that fully autonomous forest machines, capable of harvesting, processing, and forwarding log assortments, will be coming to market anytime soon. Since many factors affect productivity in timber harvesting, and the since operator has the most important role in coordinating these work systems, future investigations should focus on the assessing the efficiency of additional operator assistance systems under changing conditions. The scientific focus on job satisfaction of forest machine operators and how operator assistance can support job satisfaction, will also be of great importance in the coming years. One of the key concerns for many industries in Germany today and in the near future is the sustainable recruitment of young, well-qualified workers. A pleasant work environment and a fulfilling job, supported by dosed and well-placed elements of digitalization, under competitive salary and high employee appreciation, could help to remedy the shortage of skilled workers and prepare the forestry sector for future.

7. Publications and conference contributions

During the period of work for the doctoral thesis, the following articles and conference contributions were published.

Publications

Hartsch, F.; Schönauer, M.; Pohle, C.; Breinig, L.; Wagner, T.; Jaeger, D. (2023) Influence of Boom-tip Control and a Rotating Cabin on Loading Efficiency of a Forwarder: A Pilot Study. *Croatian Journal of Forest Engineering* (article accepted, expected publication in the end of 2023).

Dreger, F.A.; Englund, M.; **Hartsch, F.**; Wagner, T.; Jaeger, D.; Björheden, R.; Rinkenauer, G. Hierarchical Task Analysis (HTA) for Application Research on Operator Work Practices and the Design of Training and Support Systems for Forestry Harvester. *Forests* **2023**, *14*, 424. https://doi.org/10.3390/f14020424

Hartsch, F.; Schönauer, M.; Breinig, L.; Jaeger, D. (2022): Influence of Loading Distance, Loading Angle and Log Orientation on Time Consumption of Forwarder Loading Cycles: A Pilot Case Study. *Forests* **2022**, 13, 384. https://doi.org/10.3390/ f13030384

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Huber, M.; Hoffmann, S.; Brieger, F.; **Hartsch, F.**; Jaeger, D.; Sauter, U.H. (2021): Vibration and Noise Exposure during Pre-Commercial Thinning Operations: What Are the Ergonomic Benefits of the Latest Generation Professional-Grade Battery-Powered Chainsaws? *Forests* **2021**, 12, 1120. https://doi.org/10.3390/f12081120

Hartsch, F.; Jaeger, D.; Jordan, T. (2021): Wertästung 2.0. *Forst und Technik* 04/2021, pp. 38-43.

<u>Conference Contributions</u>

Hartsch, F. (2023): Stand der Technik von Assistenzsystemen bei Forstmaschinen. Presentation at *VDI Seminar, Kölner Bezirksverein e.V. des VDI and Institut für Bau- und Landmaschinentechnik*, TH Köln. Köln, Germany.

Hartsch, F.; Wagner, T.; Jaeger, D. (2022): Arbeitsweisen von Forstmaschinenführern – Häufige Fehler und Verbesserungsmöglichkeiten. Presentation at *Forstunternehmertag of Interforst – Leitmesse für Forsttechnik*. München, Germany.

Hartsch, F. (2022): Wem gehören eigentlich Forstmaschinendaten? Presentation at *„Runder Tisch Datenschatz Forstmaschine"*. Kuratorium für Waldarbeit und Forsttechnik e.V. Groß-Umstadt, Germany.

Hartsch, F.; Schönauer, M.; Breinig, L.; Jaeger, D. (2021): Der Einfluss von Ladeentfernung, Ladewinkel und Ablagewinkel von Rundholzabschnitten auf die Dauer von Forwarder-Ladezyklen: Eine Pilotstudie. *Forstwissenschaftliche Tagung 2021*. Freising, Germany.

Huber, M.; Hoffmann, S.; Brieger, F.; **Hartsch, F.**; Jaeger, D.; Sauter, U.H. (2021): Vibrations- und Lärmexposition während der Jungbestandspflege: Was sind die ergonomischen Vorteile akkubetriebener Motorsägen? *Forstwissenschaftliche Tagung 2021*. Freising, Germany.

Hartsch, F.; Jaeger, D.; Jordan, T. (2021): Fully Mechanized Pruning with the PATAS Module – A Joint Study in Northern Germany on Productivity and Ergonomics. *International Symposium on Forest Mechanization 2021*. Corvallis, Oregon, USA.

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Kemmerer, J.; **Hartsch, F.**; Breinig, L.; Labelle, E.R. (2019): Legal, Social and Economic Requirements for Integration of Harvester Data in Logistics Chains in Germany. *International Symposium on Forest Mechanization 2019*. Sopron, Hungary.

8. Curriculum vitae

Personal details

Name	Florian Hartsch
Gender	Male
Citizenship	German
Date of birth	09th of June, 1993
Place of birth	Hildesheim
E-mail	florian.hartsch@gmx.de

Education and Work Experience

Since 06/2023	Forest official trainee (higher service)
	Northrhine-Westfalian State Forest Service
01/2020 – 05/2023	Research associate (50%)
	Northrhine-Westfalian State Forest Service
	Center for Forest and Timber Industry
	Forest Education Center
04/2019 – 05/2023	Research associate (50%)
	University of Göttingen
	Faculty of Forest Sciences and Forest Ecology
	Department of Forest Work Science and Engineering
10/2017 – 03/2019	Master program “Forest and Wood Sciences” (Academic degree: M.Sc.)
	Technical University of Munich (TUM)

10/2014 – 03/2018	Bachelor program “Forest Sciences and Forest Ecology” (Academic degree: B.Sc.) University of Göttingen
08/2012 – 07/2014	Forest worker trainee (Professional degree: “Forstwirt”) State Forest Service Saxony-Anhalt Harz Forest District
08/2011 – 07/2012	Ecological voluntary service (“Freiwilliges Ökologisches Jahr”) Harz National Park
2011	High school graduation (“Abitur”) Bischöfliches Gymnasium Josephinum Hildesheim

Research experience

04/2019 – 10/2022	Project: Advanced Virtual Aptitude and Training Application in Real Time. Scope: Development of digital operator assistance systems. Funding: European Union´s research and innovation program “Horizon 2020” via Fachagentur Nachwachsende Rohstoffe e.V. (FNR). Grant agreement no. 773324.
11/2022 – 05/2023	Project: Klimasmarte Wege für klimafitte Wälder (KlarWeg). Scope: Adapted forest road management due to climate change. Funding: BMEL and BMU´s funding program “Waldklimafonds” via Fachagentur Nachwachsende Rohstoffe e.V. (FNR). Grant agreement no. 7030365.

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Total of 169 References.

10. Appendix

10.1 Declaration of originality

I hereby confirm that I have written this thesis independently without any outside support and that I have only used the references which are given in the text. I have marked the passages taken verbatim or in spirit from other works by marking the sources. I followed the guidelines for the assurance of good scientific practice at the University of Göttingen. If a digital version of this thesis has been submitted, it agrees with this version. I am aware that in case of violation of these principles the exam will be graded as failed.

Göttingen, November 2023

Florian Hartsch