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New configurations of the tele-extraction concept

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ABSTRACT

Within cut-to-length forwarding, a theoretical semi-autonomous teleoperation concept called tele-extraction, with automation of crane work and teleoperation of driving, was modeled and simulated. Both configurations modeled had greater potential for cost reduction than a previously studied alternative where the driving was automated, and crane work was teleoperated. Teledrive with teleoperated driving empty, driving loaded, and driving between log piles while loading, showed a reduced cost of 10% for five operators on ten forwarders, whereas teledrive with both loading and driving while loading automated showed a reduced cost of 18% at four operators. In both configurations, the lowest cost was reached at about 10% lower productivity compared to standard forwarding. Increased extraction distance had a negative impact on potential for cost reduction since the driving was teleoperated while terminal activities were autonomous.

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forwarding; CTL; teleoperation; automation; discrete event simulation; organization

Introduction

Cut-to-length (CTL) harvesting performed using a mechanized harvester and forwarder system is common in forestry (Lundbäck et al. 2021). Further development of this system is focused on smart technology for operator support and eventual full autonomy (Lindroos et al. 2019; Manner et al. 2019). To guide research efforts toward full autonomy, simulations of future concepts are important (cf. Johnson and Fisher 1978; Asikainen 2010; Ringdahl et al. 2012; Dong et al. 2020). Automation scenarios such as remote supervision, semi-autonomous harvesters, and autonomous wood shuttles have been discussed (Hellström et al. 2009). For forwarding, standard work elements remain the same regardless of the level of automation or teleoperation, including driving empty, loading, driving between log piles, driving loaded, and unloading (c.f. Nurminen et al. 2006), all contributing to the extraction of a full load of logs. Downtime or delays occur during this work for various reasons.

The first attempts at teleoperation occurred in the mid-1940s in the form of a mechanically controlled master – slave teleoperation, later developed into electrical servo control (Hokayem and Spong 2006). More sophisticated teleoperation will inevitably demand increased amounts of data transfer between the teleoperator and the remote environment. A way to reduce the need for data transfer during teleoperation is to increase the level of autonomy of the vehicle or robot that is remotely controlled, when solely giving high-level directions a longer transfer delay can also be accepted (cf. Materna et al. 2017; Young and Peschel 2020). The general issues of signal transfer and delays in teleoperation are particularly relevant for forestry applications due to the often large and very remote working areas. The tele-robotics field has a widely held belief that higher levels of automation result in more efficient and easier teleoperation (Niemeyer et al. 2016). As full automation currently remains technically challenging to achieve, teleoperation will play a crucial role in enabling the automation of forestry.

A short-range teleoperated harvester prototype was tested and rejected in Sweden (Bergkvist et al. 2006) with outcomes congruent with system-wide analysis (Lindroos 2012). A theoretical semi-autonomous forwarder concept named tele-extraction has also been analyzed (Lundbäck et al. 2022). This tele-extraction concept involves the forwarder autonomously driving from the landing to the harvest area and back to the landing with an empty or full load space, respectively. Loading, driving between log piles, and unloading (including driving during unloading), were teleoperated from a remote location, enabling teleoperators to operate different machines on an as-needed basis. Tele-extraction demonstrated potential cost savings of 6–8% compared to standard forwarding when 7 teleoperators were responsible for 10 machines. However, the precise work elements first to be automated are unclear, pushing the evaluation of other tele-extraction configurations. Moreover, the tele-extraction concept assumes that an on-site operator is unnecessary for daily forwarder operation, except for maintenance tasks. This increases the design flexibility of the machine, and the operator's cabin can be removed entirely, allowing for more space and weight for payload.

This study aimed to compare the economic potential of specific *teledrive* configurations, involving teleoperation of various driving work elements of the tele-extraction concept, to standard forwarding. The expectation of higher economic potential for the teledrive configurations compared to other tele-extraction configurations and standard forwarding stemmed from variations in the average time consumption for different work elements.

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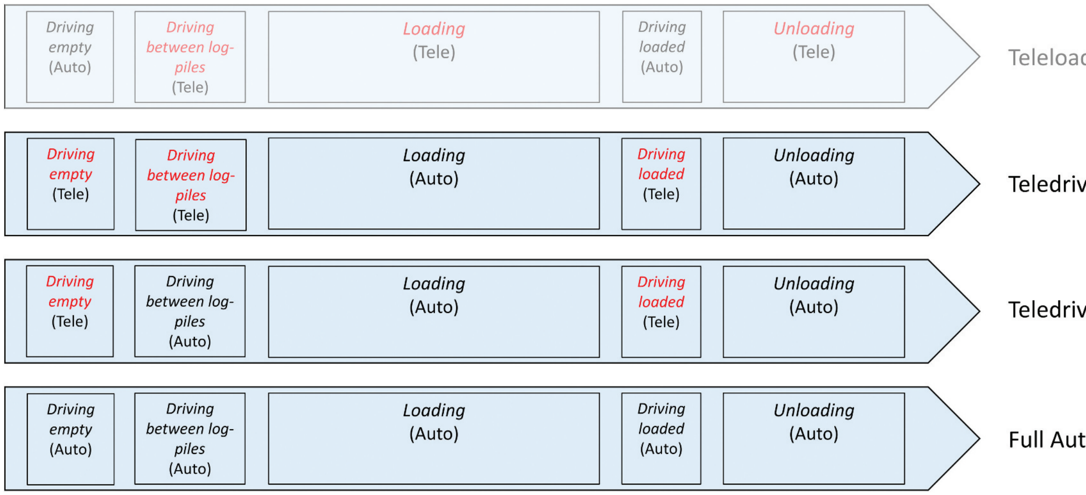
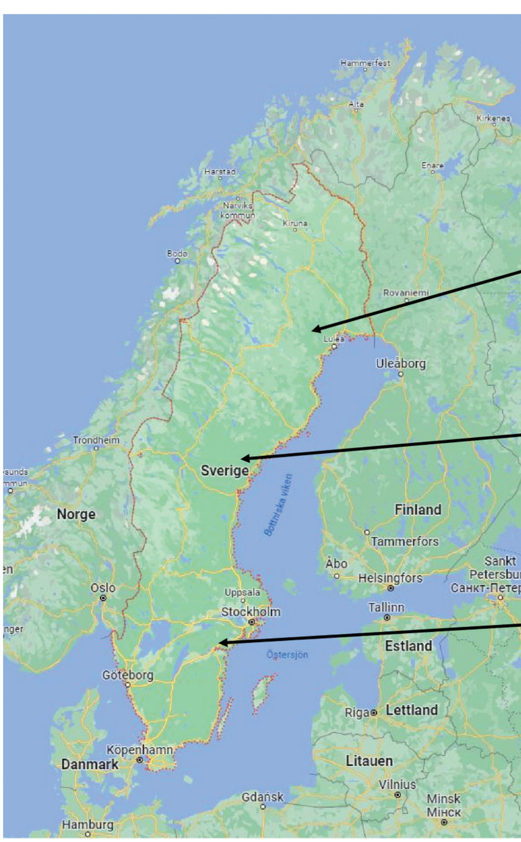


Figure 1. Conceptual illustration of the different configurations of tele-extraction. "Teleload" was simulated in Lundbäck et al. (2022) and Teledrives A and B were simulated in this study, with Full Auto as the ultimate reference point. The width of the box with each work element corresponds to the average productive machine hour (PMH) time for that work element as a share of the total PMH time per forwarder load according to Manner et al. (2016). Red text indicates that the work element was teleoperated.

Materials and methods

In this study, two specific theoretical configurations of the tele-extraction forwarding concept were simulated. In the first configuration, Teledrive A, the work elements driving empty, driving loaded, and driving while loading (between log piles) were teleoperated and loading and unloading were autonomous. This configuration implies frequent shifts between machines for operators of many simultaneous machines, since the driving between log piles was teleoperated while the loading crane work was autonomous (Figure 1). In the second configuration, Teledrive B, driving empty and driving loaded were teleoperated while loading, driving while loading (between log piles), and unloading were autonomous. Teledrive B differed from Teledrive A in that driving while loading was autonomous (Figure 1). A third configuration, Full Auto, was used as reference; all work elements were autonomous and no operators were



	Sum	Average	Std. Dev.	Min	Max
North					
Number of stands	164	-	-	-	-
Total volume (m³ sub)	316 904	1 932	1 597	162	9 022
Harvested volume (m³ sub/ha)	-	192	94	105	730
Mean stem size (m³ sub)	-	0.24	0.08	0.10	0.48
Extraction distance (m)	-	351	225	100	1 400
Middle					
Number of stands	162	-	-	-	-
Total volume (m³ sub)	310 801	1 919	2 849	72	14 875
Harvested volume (m³ sub/ha)	-	272	93	102	683
Mean stem size (m³ sub)	-	0.35	0.13	0.09	0.77
Extraction distance (m)	-	451	304	70	1 500
South					
Number of stands	801	-	-	-	-
Total volume (m³ sub)	992 859	1 240	1 320	105	13 664
Harvested volume (m³ sub/ha)	-	236	116	100	952
Mean stem size (m³ sub)	-	0.46	0.18	0.10	2.78
Extraction distance (m)	-	359	180	20	1 300

Figure 2. Approximate location and key figures of the harvest areas included in the study.

needed, i.e. removing the operator cost while keeping productivity similar (Figure 1). Hence, Full Auto represented the greatest potential cost reduction in this study.

Stand data

The simulation models used in this study were developed from the tele-extraction model set out in Lundbäck et al. (2022). The input stand database was identical between simulations, with randomized stand order between the machines. The database contained 1,343 stands from real final fellings in three regions of Sweden, harvested volumes between 100 and 1,000 m^3 sub/ha (solid cubic meters under bark per hectare), mean stem sizes between 0.10 and ~1 m^3 sub, and extraction distances of between 20 and 1,500 meters one way (Figure 2). After initial test simulations, only data from the "North" area was further used. For more details see Lundbäck et al. (2022).

Simulation

The development of the discrete event simulation models and succeeding simulations were done with the simulation software AnyLogic 8 University (8.7.2). Post-processing of simulation outputs were done with the statistical software R, version 4.0.2 (R Core Team 2018). For further descriptions of the exact workflow see Appendix and Lundbäck et al. (2022).

The forwarding involved five work elements (Figure 3) and downtime, each with separate time consumption functions. The total time for each load was calculated by adding the simulated time for the five work elements and the separately recorded downtime (Eq 1), which was modeled based on real follow-up machine data provided by a large forest company, from 31 forwarders operating between June 2019 and May 2020 in northern Sweden.

$$T_{total} = T_{DE} + T_L + T_{DL} + T_{DF} + T_U + T_O \tag{1}$$

where:

- T_{DE} Time for driving with empty loadspace from landing to where the loading begins,
- T_L Time for loading (including simultaneous crane work and driving),
- T_{DL} Time for driving while loading (when the crane is resting),
- T_{DF} Time for driving with full load from where loading was finished to landing,
- T_U Time for unloading,
- T_O Other time, also referred to as delays or nonproductive machine time.

The productivity was then calculated based on a load size of 22 m^3 sub of roundwood (Figure S12), or 24 m^3. The larger load volume was simulating payload instead of the operator's cab. Thus, input stand data was recalculated accordingly, resulting in fewer loads per harvested stand.

Downtime as well as driving speeds and distances within harvest areas were treated as random elements in the simulation model (Table 1). Time consumption functions in the models were based on previous studies (Nurminen et al. 2006; Lindroos 2012), driving distances with and without load, D_{DE} and D_{DF}, respectively, were assumed to be the same (Eq. 2), and all extracted wood was assumed to be one single sawlog assortment.

$$D_{DE} = D_{DF} = D_{ED} - \frac{D_{DL}}{2} \tag{2}$$

where:

- D_{ED} One way extraction distance estimated by forestry professionals before harvesting,
- D_{DL} Distance driven during loading.

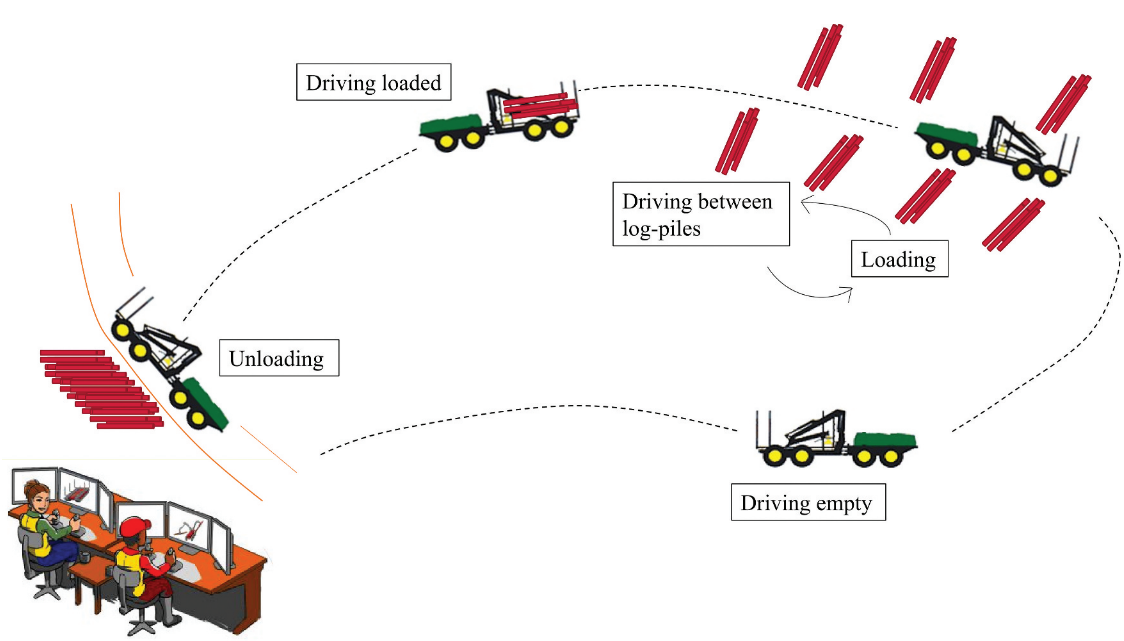


Figure 3. Illustration of the main work elements within forwarding in a teleoperation setting (drawings by Mikael Lundbäck, Ola Lindroos, and Skogforsk).

Table 1. Application of probability density functions and their parameters in the simulations (Lundbäck et al. 2022.).

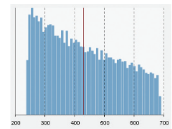
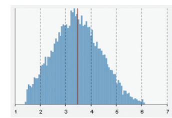
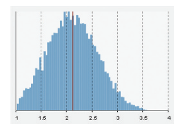
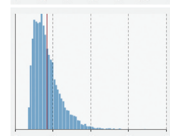
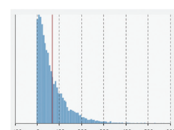
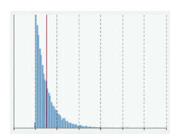
Application	Function	Parameters	Truncation	Visualization	Comment
Driving empty and loaded distances (m)	Exponential distribution	Mean (scale) = de, shift (threshold) = 1	$\min = d_e - \frac{\sqrt{V_{tot}/v \times 10000}}{2}$ $\max = d_e + (d_e - \min)$ where d_e= driving empty, v = harvested volume/ha, V_{tot} = harvest plot total size (m^3)		Example visualization: Extraction distance = 500 m, v = 250 m^3, V_{tot} = 5 000 m^3
Driving empty speed (km/h)	Normal distribution	Mean = 3.4, Standard deviation = 1	min = 1.44, max = 6.12		
Driving while loading speed (km/h)	Normal distribution	Mean = 2.1, Standard deviation = .5	min = 1.04, max = 3.6		
Unloading time (minutes)	Erlang distribution (special case of the Gamma distribution)	beta = 2.5, *m* = 2	min = 3.5		
Downtime occurance (minutes)	Exponential distribution	Mean (scale) = 68, shift (threshold) = 0	min = 0, max = 1000		
Downtime duration (minutes)	Exponential distribution	Mean (scale) = 10, shift (threshold) = 0	min = 0, max = 450		

Table 2. The variation of operator cost and time consumption for automated work elements parameters.

		Sensitivity analysis			
Parameter	Unit	Baseline	Min	Max	Step
Operator cost	\$/SMH	43.6	21.9	65.6	10.9
	%	100	50	150	25
Time consumption automation	%	100	50	150	25

To model Teledrive A, with automated loading and teleoperated driving between log piles, the original tele-extraction simulation model in Lundbäck et al. (2022) was augmented with a new local loop structure for the loading work element. The loop iterated through the loading and driving between log piles work elements until the target number of crane cycles for each load were completed. The target number of crane cycles was selected from a normal distribution with average and tails derived from statistics in Manner et al. (2016). This structure enabled the operator to be seized and released for every change between loading and driving between log piles. The operators were also seized for the work elements driving empty and driving loaded, and the release function was applied when the work element was finished.

Costing

To evaluate the economic potential of different configurations, simulation results were compared against the simulation of standard forwarding conducted by Lundbäck et al. (2022). All cost parameters were assumed equal in both standard forwarding and tele-extraction, except for the total cost of the operator. The total cost of the operator varied with operator time per load, 100% in the standard case and less in the tele-extraction cases. This implies that the chosen level of operator cost per hour affects the comparison of the economic potential. The cost analysis involved combining hourly cost components based on the COST-model (Ackerman et al. 2014), as outlined below, and multiplying them by time consumption before dividing by volume (Figure S12). While delay time did not have variable machine costs, it did have fixed machine and operator costs factored in. The assumptions and calculations made in the COST-model resulted in a fixed machine cost of 29.5 USD/Scheduled machine hour (SMH), variable machine cost of 50.4 USD/SMH, and operator cost of 43.6 USD/SMH, which are typical levels for large forwarders and salaries in Swedish forestry. SMH did not include breaks, meals, or relocations, but it did include technical machine downtime such as time for repairs and maintenance.

Sensitivity analyses

The main features that affect the costs when comparing standard forwarding with tele-extraction was the operator cost and the time spent on work elements with vs without operator involvement. All other bases for productivity and cost calculations were held constant regardless of configuration. To address variations in operator cost, now and in the future, as well as uncertainties regarding actual productivity in autonomous and operator-controlled work elements, respectively, sensitivity analyses were performed. In the sensitivity analyses, the time consumption and operator cost parameters were varied from 50% to 150% of baseline (Table 2).

Results

In general, all configurations in this study showed a higher potential cost reduction compared to previously evaluated tele-extraction configurations (Lundbäck et al. 2022). Productivity steadily decreased with the number of operators, accelerating below 5 (Table 3). Regarding cost, the optimal number of operators was 4 to 6 depending on configuration (Table 3). Only the north region is shown since results from middle and south were repetitions of similar patterns.

Utilization and productivity

Machine utilization was stable at the level given by technical availability and modeled delays for Full Auto and Full Tele. With partly automated configurations and fewer teleoperators, machine utilization declined in the same pattern as productivity. Simultaneously, the utilization of the operator pool increased as the operators that were still present got busier and busier (Figure 4). Compared to the Teledrive A configuration, operator and machine utilization curves for Teledrive B crossed each other at a lower number of operators; this is logical since Teledrive B includes more automation (also the driving between log piles).

Extraction cost reduction

In line with previous simulations, there was a logical pattern of decreasing operator cost with fewer operators, however, only to a certain point (Figure 5). The fixed machine cost per m^3 increased with decreased productivity (at low number of operators), and the operator cost per m^3 actually increased when there are only 1–2 operators in the Teledrive A configuration (Figure 5); this was an effect of the extremely low productivity (Table 3).

Teledrives A and B showed potential cost reductions of 10% and 18%, respectively, compared to standard forwarding at normal extraction distances in the north region (Figure 6).

Table 3. Productivity (m^3 sub/SMH) and cost (USD/m^3 sub), average with standard deviation in parentheses and median with inter-quartile range (Q3–Q1) in parentheses, for Teledrive A (teleoperated driving between log piles) and Teledrive B at different number of operators on ten forwarders.

Number of operators	Full Tele (10)	9	8	7	6	5	4	3	2	1	Full Auto (0)
Teledrive A											
North Region											
Productivity average (std. dev.)	30.47 (11.21)	30.44 (11.23)	30.44 (11.20)	30.17 (11.02)	29.23 (10.61)	26.92 (9.53)	22.76 (7.83)	17.02 (5.73)	10.38 (3.36)	4.18 (1.20)	31.44 (10.87)
Productivity median (IQR)	34.09 (14.86)	34.10 (14.80)	34.06 (14.83)	33.71 (14.63)	32.52 (13.98)	29.53 (12.92)	24.52 (10.92)	18.01 (8.23)	10.81 (4.88)	4.29 (1.71)	34.74 (14.49)
Cost average (std. dev.)	3.73 (.71)	3.59 (.71)	3.45 (.71)	3.32 (.70)	3.23 (.71)	**3.23** (.72)	3.37 (.75)	3.79 (.83)	4.91 (1.08)	9.10 (2.03)	2.25 (.69)
Cost median (IQR)	3.55 (.80)	3.40 (.79)	3.26 (.79)	3.14 (.79)	3.05 (.80)	3.05 (.82)	3.20 (.88)	3.63 (1.02)	4.77 (1.40)	8.94 (2.73)	2.08 (.77)
Teledrive B											
North Region											
Productivity average (std. dev.)	31.09 (11.13)	31.09 (11.20)	31.04 (11.17)	30.98 (11.21)	30.86 (11.02)	30.24 (10.66)	28.45 (9.66)	24.55 (7.87)	18.03 (5.41)	9.42 (2.70)	31.44 (10.87)
Productivity median (IQR)	34.57 (14.85)	34.59 (14.87)	34.53 (14.86)	34.50 (14.90)	34.24 (14.62)	33.42 (14.14)	30.94 (13.14)	26.10 (11.00)	18.74 (7.75)	9.66 (3.88)	34.74 (14.49)
Cost average (std. dev.)	3.67 (.70)	3.53 (.70)	3.39 (.70)	3.26 (.70)	3.12 (.70)	3.01 (.70)	**2.96** (.70)	3.04 (.72)	3.40 (.77)	4.80 (1.05)	2.25 (.69)
Cost median (IQR)	3.49 (.78)	3.35 (.78)	3.21 (.78)	3.07 (.79)	2.94 (.78)	2.83 (.78)	2.79 (.79)	2.87 (.82)	3.26 (.93)	4.68 (1.38)	2.08 (.77)

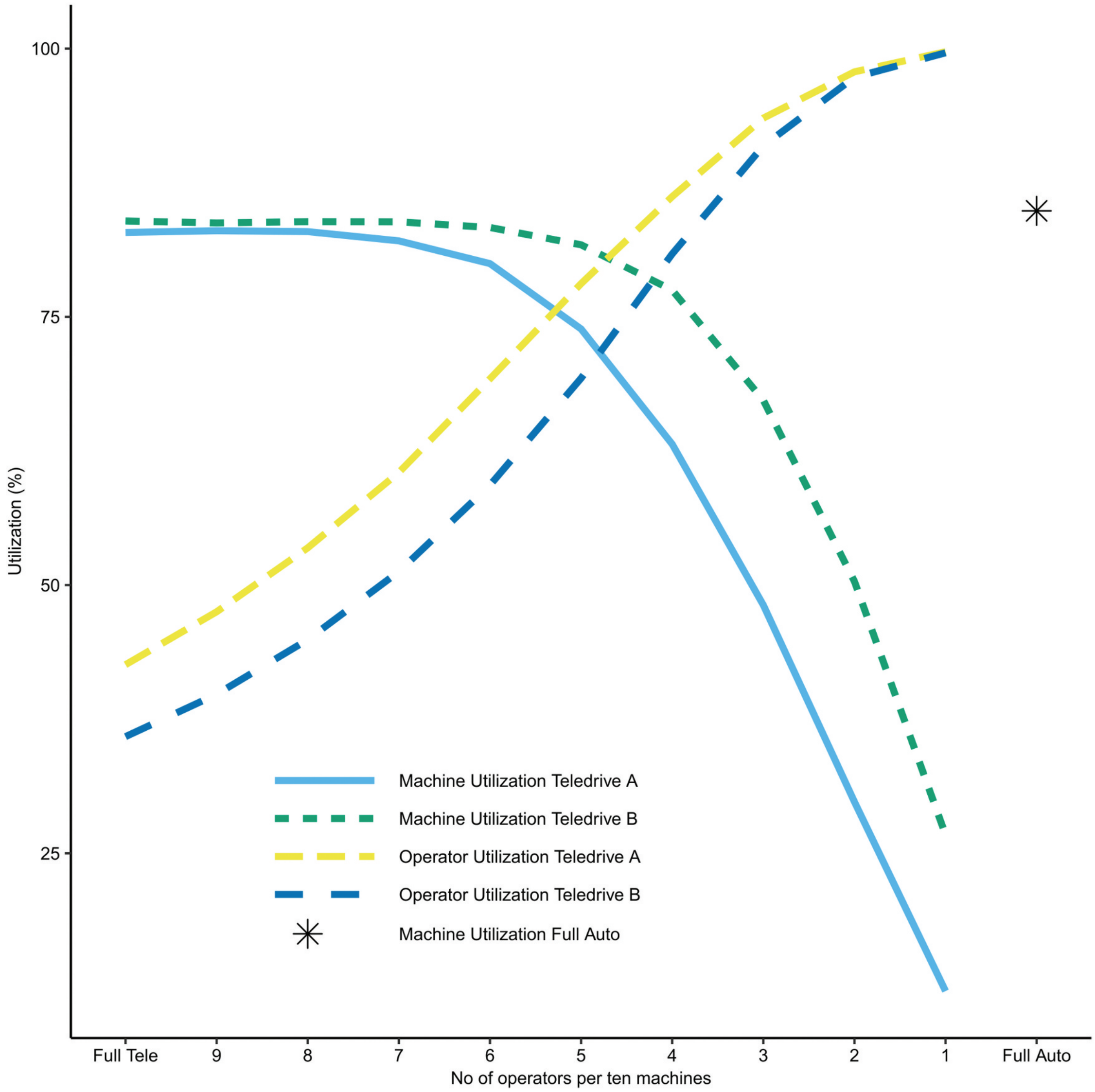


Figure 4. Average utilization of machines and operator pool for different number of operators (x-axis) and different configurations (Teledrive A and Teledrive B) with Full Auto as reference (*). North region.

Short extraction distances provided the greatest potential for cost reduction in teledrive configurations. Teledrive B had a higher potential cost reduction than Teledrive A due to more automated work elements. The Full Auto system had 38% lower cost than the Full Tele due to no operator cost, representing a theoretical maximum in potential cost reduction (Figure 6).

Sensitivity analyses

Increased operator cost resulted in increased potential cost reduction and vice versa for the tele-extraction configurations. The potential cost reduction gets close to zero with 50% reduced operator cost in the Teledrive A configuration (Figure 7, left panel). When the time consumption of automated work elements was increased, the potential cost reduction compared to standard forwarding decreased. With 50% higher time consumption for automated work elements in the Teledrive A configuration, the potential cost reduction was only about 2%, while Teledrive B kept its larger potential due to more automated time in total (Figure 7, right panel). With decreased time consumption for the automated work elements, the potential cost reduction increased by a couple of percentage points.

When increasing the payload to 24 m^3, i.e. simulating replacing the weight of the cab with payload, the average cost per m^3 could be reduced by 3–7% depending on configuration and number of operators. For the optimal number of operators in Teledrives A and B, the cost reduction was between **4–5%**, added to the original cost saving of 10–18%.

Discussion

This study explored the theoretical economic potential of tele-extraction in two variations of the Teledrive configuration, i.e. teleoperation of the driving work elements and automation of terminal activities within forwarding. It also investigated the corresponding potential of full automation, i.e. no operator involved at all. The results are novel since, to our knowledge, there are no similar, high-level studies analyzing the theoretical

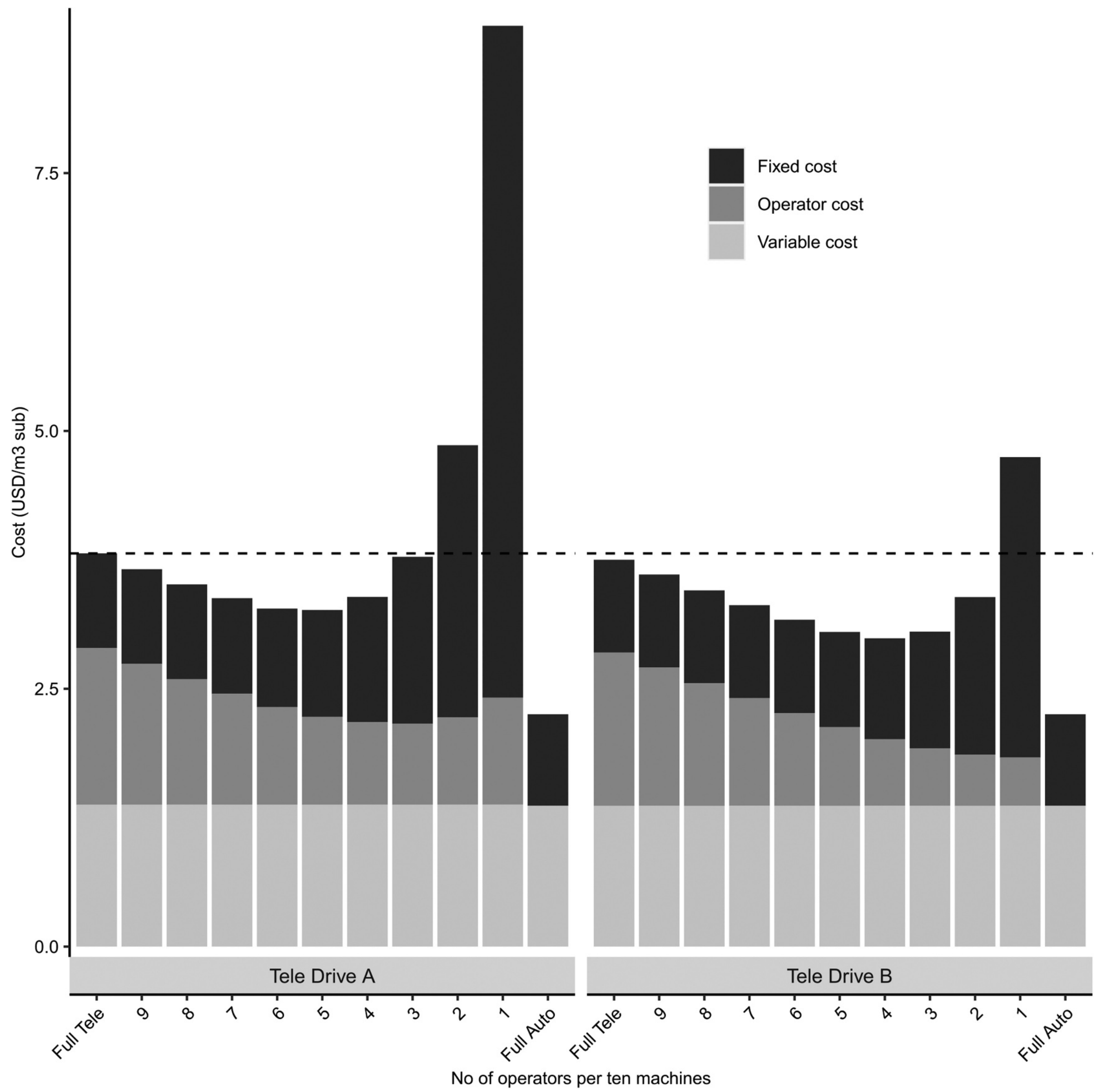


Figure 5. Average forwarder cost (USD/m^3 sub) per cost category with varying number of teleoperators (x-axis) and different configurations (Teledrive A and Teledrive B) with Full Auto as reference. North region.

potential of semi-automation aided by teleoperation in forestry. At the same time, semi- and full automation of forest operations is the goal for many projects and studies (e.g. Geiger et al. 2020; Andersson et al. 2021; Jelavic et al. 2021; Li and Lideskog 2022; Wiberg et al. 2022). This study built on a previous study of tele-extraction (Lundbäck et al. 2022), and together this body of research constitutes a comprehensive evaluation of the theoretical economic potential of certain technological and organizational development of forwarding work. The results are intended to be used by researchers and equipment manufacturers as guidelines when making decisions on resource allocation for technical development of future forwarders. Depending on the configuration, a concept such as tele-extraction has different potential gains, but also come with different technical challenges and investment requirements. None of the investment costs or technical challenges have been considered in this research. Here, the gross potential of reorganizing operator´s work in order to reduce the operator time required to extract roundwood is what was studied. Secondary effects like e.g. investment costs, technical issues, changes in productivity, ergonomic effects, and new salary levels are important subjects for future studies. Nevertheless, to have an idea of the effect from changes in some additional parameters, a number of explorative sensitivity analyses were conducted.

Additional sensitivity analyses

This study also theoretically tested to improve the weight distribution of the payload, motor, and crane in a large forwarder by adopting a new design that eliminates the cab and divides the payload into two bunks with the crane positioned in the middle. This design allows for an additional two solid m^3 under bark (m^3 sub) of payload, which roughly corresponds to the weight of the cab and its damping equipment. This improved design decreased the average cost by 3–7% depending on configuration and number of operators. This reduction in cost is not directly linked to the comparison of tele-extraction and standard forwarding, but rather has been the driving force behind the historical trend toward larger forwarders. With tele-extraction, increased payload can be

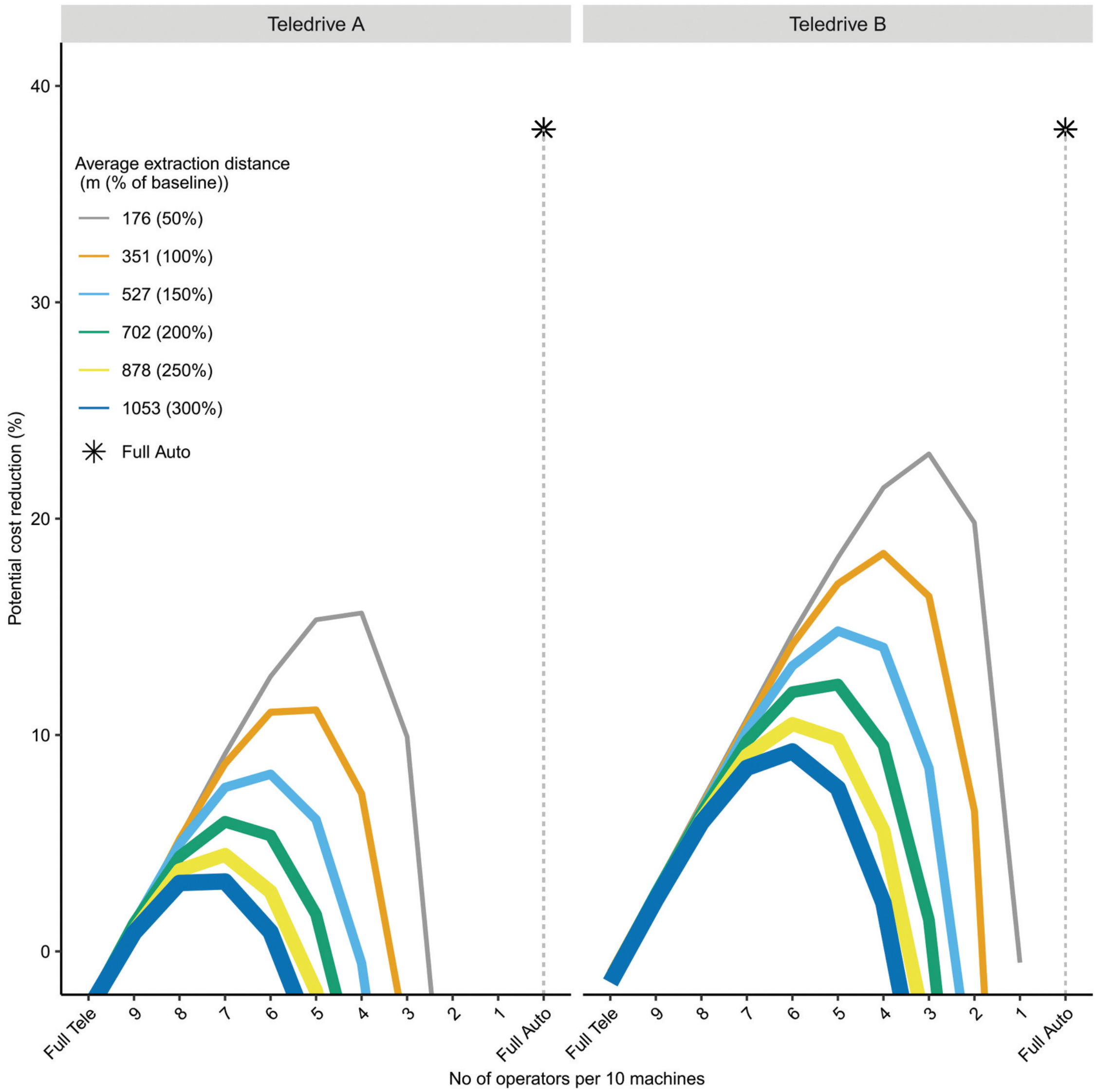


Figure 6. Simulated potential cost reductions for tele-extraction compared to standard forwarding, north region, with varying number of teleoperators (x-axis), relatively adjusted extraction distances, and different configurations (Teledrive A and Teledrive B) with Full Auto as reference (*). Most lines continue below the x-axis when number of operators decreases, spiking again for Full Auto (black stars).

achieved while maintaining the same total weight, or conversely, a lower total weight can be attained while retaining the same payload, which may be desirable in a future where warmer weather and reduced bearing capacity on forest soils are expected.

In order to achieve autonomous crane work during loading but teleoperated driving between log piles, an operator is required to enter the machine about 35 times on average before reaching a full load, which amounts to once every 30 seconds. As such, there are very short-time windows available for both teleoperation and autonomous driving, and it is likely that a remotely situated operator would need a certain amount of time to assess the situation each time the operator enters the machine to start working in a new setting. Moreover, the operators might be inhibited by transient or long-term switching effects that make their responses slower and more error-prone. Previous studies have shown that switching between tasks significantly increases task performance time and the number of errors, and also has negative and positive priming effects from previous tasks (Rogers and Monsell 1995; Monsell 2003). In the case of teleoperated forest machines, a simulation was run to quantify a switch cost of on average 10 seconds, which resulted in a decrease in productivity and an increase in cost of about **2%**, leading to cost reductions of 8% compared to standard forwarding instead of the 10% without preparation time. Hence, a system with short and frequent teleoperated work elements would require sophisticated operator support systems to minimize preparation time. A more practical configuration for implementation would be either Teledrive B, with both loading and driving while loading autonomous, or tele-extraction with autonomous driving.

In a scenario of future salary raises, this study shows that a higher operator cost will increase the potential cost reduction for tele-extraction compared to standard forwarding because it is operator time that is reduced. However, if the work is outsourced, tele-extraction is a prerequisite to access the low-waged workforce of another country, so comparisons of standard forwarding with low operator costs and tele-extraction with low operator costs are irrelevant.

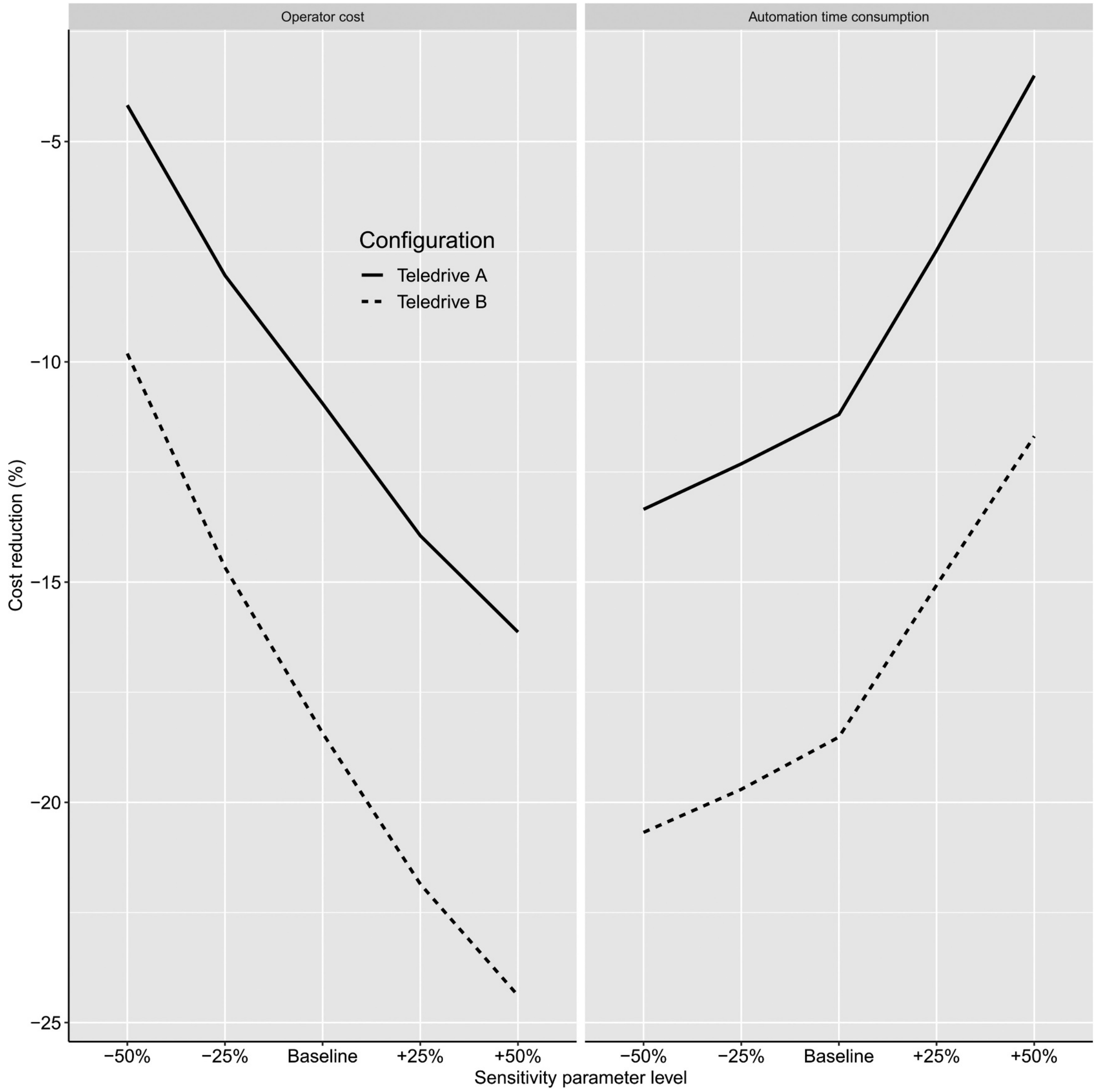


Figure 7. Sensitivity analyses of the parameters "Operator cost" and "Time consumption for automated work elements compared to their teleoperated equivalents".

This study assumed no significant difference in productivity, difficulty level, and long-term fatigue for operators, or overall machine performance and safety, between teleoperation and regular on-site operation. This assumption facilitated the identification of essential differences in forwarding systems concerning introduced waiting times when decreasing the number of operators in tele-extraction. It is important to investigate the purely theoretical potential of a new system in itself, before introducing practical implications (that may not be well known) into the analysis, cf. Lindroos (2012): that theoretical system potential is what was studied here. This kind of baseline regarding system potential can be modified later and form subject for new studies with different out-takes and approaches to certain details in the system, such as increased or decreased time consumption for teleoperation compared to on-site operation. Moreover, if future research or experience reveals significant differences in time consumption for specific work elements between teleoperation and standard forwarding, such differences could be conveniently incorporated into new simulations.

Technical aspects

The simulation approach allows for comparing virtually endless numbers of scenarios at a relatively low cost and effort while maintaining stability in parameters not studied. The results produced by the simulations are realistic enough for the study purpose but theoretically stringent with respect to confounding variables. Although the standard forwarding model used in this study was highly comparable to physical forwarding in Sweden in terms of productivity and cost, it included certain simplifications that could be considered unrealistic in some contexts. For instance, the model only accounted for one assortment, whereas four to five assortments of saw- and pulp logs are typically forwarded in Sweden and the Nordic countries. The authors, however, emphasize that the relative differences between simulations are most interesting when comparing the economic potential of new systems with the present, not the absolute levels of productivity or cost.

The time consumption and productivity of Teledrive with ten operators and Full Auto configuration were expected to be similar in the standard scenario, but instead showed a difference. Both had identical structures except for the seizing and releasing operators in Teledrive. To investigate this, the downtime functions for the forwarders were omitted in both models, leading to a reduced time consumption difference from 3.8% to 1.4%. Replacing the normal distribution function for the number of crane cycles in Teledrive A with a fixed average led to a time consumption difference of 3.1%, slightly better than the original 3.8%. Simultaneously omitting both downtime and random elements in the models decreased the difference to 0.7%. This suggests that the use of random elements in the models resulted in an unexpected difference in time consumption per load.

Due to negligible regional variation in the output, the analysis and findings presented in this study are based solely on the north region, despite having access to harvest areas in three regions (Figure 2). The cost reductions presented in Figure 6 were minimally affected by regional differences, with only slight variations of a few percentage points. In contrast, the within-region variation was considerably greater than the between-region variation, leading to the conclusion that a single input dataset for the entire country might have sufficed for this particular case. Moreover, utilizing the full dataset would have increased the computational burden while potentially yielding similar conclusions.

Organizational aspects

Since the Teledrive configuration implies automation of time-consuming work elements (loading and unloading), the number of operators can be smaller than in tele-extraction configurations with autonomous driving while maintaining cost efficiency. The results for Teledrive A show substantial potential for cost reduction under certain circumstances (Figure 6); however, the prerequisites for that configuration come with the difficult practical implications for the operators as discussed in the sensitivity analysis section.

The study's method was chosen based on the assumption that a system with non-constant relations between machines and operators could lead to waiting times. Discrete event simulation was used to capture waiting times and bottlenecks, as it can handle dependencies between resources. The operator pool was modeled as a resource pool that serves machines according to need, and queuing effects were expected to affect productivity. The patterns and lengths of busy and idle time blocks will vary with the system configuration and combination of harvest plots. Operators will move between different machines, and the total mix of extraction distances and harvested volumes will determine their workflow. The Teledrive A configuration had many short busy periods due to frequent alternation between loading crane movements and driving (Figure 8), making it more challenging to implement than other configurations. While static calculations may have reached similar conclusions, waiting times were not initially apparent. Furthermore, a simulation approach enables the developer, as well as other people involved, to observe the running model in real time which contribute to an increased understanding of both the system, the model, and their differences.

The feasibility of different configurations of autonomy for machine operations in harvest areas is contingent on the physical environment. Full automation may be achievable within a few years for straightforward harvest sites characterized by flat, smooth, and solid ground, uniform logs in regular patterns, and other similar attributes. For more complex driving or crane work, a teleoperator may be employed, with the level of autonomy determined by site-specific factors. Comparable approaches have been applied in other areas such as assistive robots for elderly care (Materna et al. 2017), which can autonomously manage some tasks while relying on teleoperation for more difficult ones. Future planning for harvest areas will likely consider physical properties, on-site difficulties, and localized network reception and quality as relevant variables for determining the level of automation. A harvest site that is relatively easy for autonomous extraction but has poor network connectivity can still be managed effectively with an autonomous tele-extraction system, just as a difficult harvest site with good network coverage could rely more heavily on teleoperation.

To determine the appropriate focus for developing a tele-extraction concept, it is crucial to consider the scale at which it would be implemented. This raises the question of whether tele-extraction is equally advantageous for a fleet of five machines as it is for 50 machines. Moreover, it is important to consider who would be willing and able to invest in and operate such a system. In Sweden, small contractor companies, which typically own only a few machines (Häggström et al. 2013), may not have the capacity to undertake such an initiative. It may be necessary to return to the historical situation where large forest industry companies own and operate their own machinery or for machine manufacturers to develop and operate systems that include machines and teleoperation

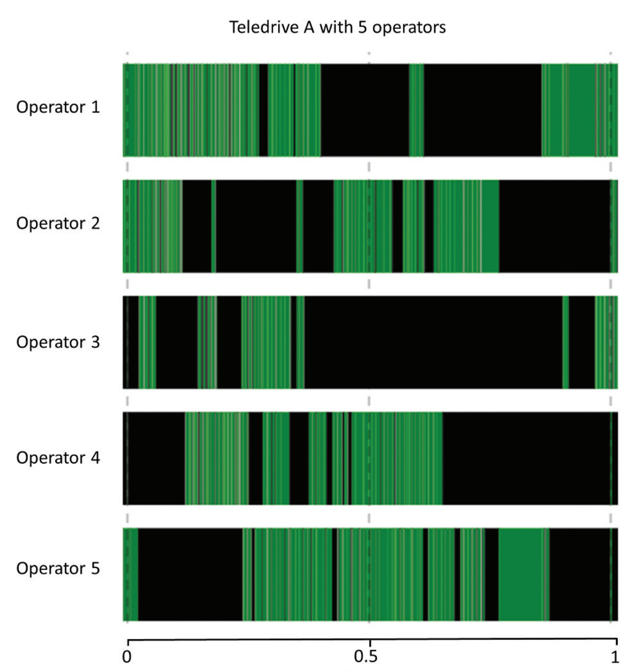


Figure 8. High-resolution visualization of a one-hour output of the Teledrive A simulation with five operators, black = busy and green = idle. The gray zones in the green areas indicate very short time windows for driving between log piles (operator busy) and loading (operator idle).

stations with personnel. These critical issues require further exploration and resolution in both theoretical research and practical harvesting operations and machine manufacturing.

Future research

There are many opportunities for further studies based on what have been discussed above, two main ones that would not be too far in the future are listed here. First, the possibility to refine the model for a Swedish context with new data about differences in time consumption depending on on-site operation, teleoperation, or autonomous operation. This could help define more in detail what scenarios are most likely to be feasible in a large-scale implementation. Second, adaption of the specific time consumption functions to local conditions could enable case studies of tele-extraction in areas with industrial pulpwood plantations, thus utilizing the drawback of only simulating one assortment to an advantage. The concept of managing a fleet of forwarders and operators, like in tele-extraction, is already in place to a large extent at the big pulp- and paper companies in, for example Brazil and South America.

Conclusions

Teledrive in different variants has the theoretical potential to be up to 18% more cost efficient than standard forwarding; and, as opposed to the previously studied tele-extraction configuration, the potential for teledrive was largest for short extraction distances since that is what results in the highest share of autonomous work during a forwarder load cycle. Sensitivity analyses of changes in operator cost, changes in time consumption for autonomous work, increased payload, and extra waiting times resulted in a variation of the theoretical potential between 3 and 24% cost reductions. The absolute maximum potential cost reduction from automation, so-called Full Auto based on equal time consumption for the same work elements, was 38%, corresponding to removing the operator cost completely.

Disclosure statement

No potential conflict of interest was reported by the authors.

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