European Journal of Forest Research (2024) 143:1667–1683
https://doi.org/10.1007/s10342-024-01713-w

RESEARCH

Trade-offs between stump-to-roadside lead time and harvesting cost, when using different number of operators in a harvester-forwarder system

Malin Johansson[1] · Mikael Lundbäck[2] · Ola Lindroos[1]

Received: 20 July 2023 / Revised: 10 June 2024 / Accepted: 18 June 2024 / Published online: 15 July 2024

Abstract
For customer-oriented wood supply, buffering is required for flexibility to handle interactions in the wood procurement system. This includes balancing lead-time and operational cost by using stocks and production capacity as buffers. Despite the well-known challenge to balance the interactions between harvesting and forwarding in Nordic mechaniced CTL-operations, there has been limited research on how the machine groups can be staffed to enable flexibility and more focus on other measures to create flexibility. Therefore, this study explored trade-offs between wood lead-time and harvesting cost in the stump-to-roadside part of the wood supply chain by altering the numer of full-time working operators in the harvesting groups. This was done using discrete-event simulations implemented in Anylogic software. Input data included information about operational conditions in 1500 forest stands. The results revealed that the best balance was to have sufficient harvesting capacity to adjust wood lead times at the expense of increased harvesting costs. Of the tested options, the best balance was achieved when staffing a two-machine group with three operators, and thereby allocating 50% of the used work-shifts to regulating the field wood stock between the two machines. This resulted in the shortest lead times and the smallest harvesting cost increase. Compared to the option with no flexibility for stock adjustment (4 operators), the average lead-time could be reduced to one tenth at a cost increase of 3.4%. These findings have the potential to improve decisions of how harvesting groups are staffed to balance specific objectives of desired lead times and costs, which migh prove to be a valuable addition to the already used measures to manage wood flow.

Keywords Logging · Flexible resources · Collaboration · Supply chain management · Buffers

Communicated by Eric R. Labelle.

✉ Malin Johansson
malin.m.johansson@storaenso.com

Mikael Lundbäck
mikael.lundback@umu.se

Ola Lindroos
ola.lindroos@slu.se

[1] Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Skogsmarksgränd, Umeå 90183, SE, Sweden

[2] The Department of Physics, Umeå University, Umeå 90187, SE, Sweden

Introduction

Flexibility in wood supply

Wood-based products are greatly desired by the market since they are both renewable and reusable. Nevertheless, the manufacture of wood products must also remain cost-competitive compared to other substitutable products. In that respect, a customer-oriented wood supply is essential, and the wood flow precision, meaning to what degree the supply rate follows the demand rate, is inherently important. The wood should be delivered to the mill (the customer in this context) with the correct quality, in the correct quantity, and at the right time. In this way, the mill can align its production with downstream needs (Carlsson and Rönnqvist 2005). Wood flow management is intrinsically complex due to features such as geographical dispersion of production sites (the forest stands), divergent flows of products, and acute sensitivity to weather and climate. This means that the wood flow is commonly and repeatedly disrupted by both anticipated and unforeseen variations (Audy et al. 2012; Guatam et al. 2009).

To ensure that the volumes demanded are delivered to the mill as desired, there is a need to match the production rate with the desired delivery rate. Therefore, the complexity and volatility of the supply chain requires buffers to achieve the necessary flexibility. These buffers can be created using two main principles – buffers in wood stock and in production capacity (Laestadius 1990; Audy et al. 2012). A wood stock buffer reduces the need for well-matched balancing between production and delivery rates, by leveling out occasional deviations as well as creating time to manage substantial variations. A production capacity buffer enables adjustment of the production rate in order to meet the demand, by changing the capacity used. Most often, both principles are used to some extent in all wood supply chains, but there can be differences in which one is dominant (Audy et al. 2012). For instance, Laestadius (1990) found that, in Sweden, the main buffer principle was to have stocks in different locations across the supply chains, whereas the main principal used in the Southern US was to have buffers in production capacity. Hence, there are real-life observations supporting the idea that these main principles both provide the desired wood supply. Both principles provide flexibility to the wood supply chain but with different strengths and weaknesses (Fig. 1).

Compared to processes that do not need substantial flexibility, flexible processes are associated with increased costs

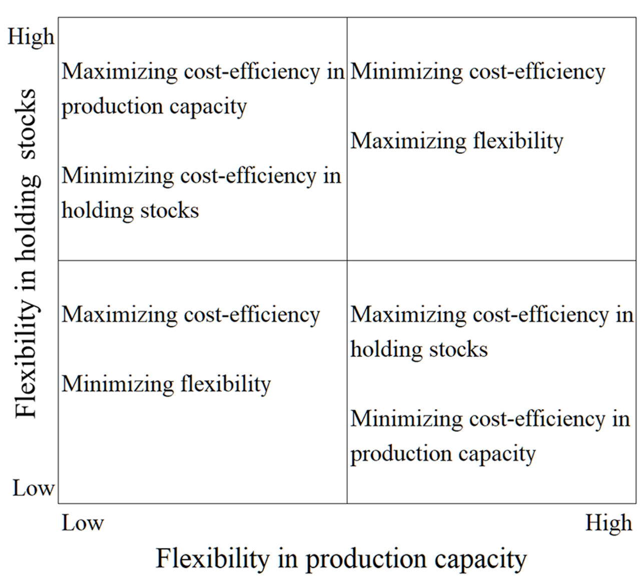


Fig. 1 Trade-offs between flexibility and cost-efficiency when using production capacity and product stocks as buffers in the wood supply chain. Based on the work of Laestadius (1990)

due to the buffering required. Hence, there is a trade-off between flexibility and cost-efficiency, so the challenge is to achieve the best balance. There are four typical combinations of the two main buffering principles (Fig. 1). With low flexibility in both stock levels and production capacity, the cost-efficiency is maximized at the expense of flexibility. In contrast, maximum flexibility for both principles comes with low cost-efficiency. In the other two combinations, with high flexibility in one principle and low flexibility in the other, the non-flexible principle is cost-efficient while the flexible one is not. However, combined with the goal to deliver wood of the right quality and in the right quantity at the right time, flexibility is needed in a suitably combined mix of the two buffer principles. As Laestadius (1990) showed, the suitable mix is context dependent and might reflect, for example, differences in labor and/or equipment costs, labor legislation, raw material deterioration rates and traditional features of the wood supply chains.

An underlying principle of supply chains is that the overall performance is the most important factor. Therefore, the buffering principles should be balanced throughout the whole supply chain, potentially leading to the best delivery service (Eliasson et al., 2022; Kogler and Rauch 2018). For trade-offs to be shared over the whole supply chain, it remains important to look at single process steps or units of the supply chain to investigate how trade-offs may affect single actors (Hansen and Justin, 2018). Research of balancing buffer principles has mainly addressed trade-offs in the later part of the wood supply chain i.e. from roadside to industry, without addressing the trade-offs in harvesting operations i.e. from stump-to-roadside (Haartveit and Fjeld 2003; Bredström et al. 2004; Carlsson and Rönnqvist 2005; Kogler and Rauch 2023). Research of cost-efficiency in harvesting operations is indeed abundant (e.g. Eriksson and Lindroos 2014; Liski et al. 2020; Lundbäck et al. 2022). Howver, there are, to the best of our knowledge, very few studies of the trade-offs between flexibility and cost-efficiency, although Helstad et al. (2001) did highlight costs and constraints for volume flexibility in harvesting operation more than 20 years ago. This shortage is somewhat surprising, considering the well-known challenge to balance the interactions between harvesting and forwarding (e.g. Lindroos 2012; Ringdahl et al. 2012). Such balancing is constantly managed in operational forestry, to provide a field stock (i.e. volume that is cut by the harvester but not yet extracted to roadside by the forwarder) large enough so that the forwarder does not run out of work when work conditions change, but small enough to handle the risk of severe complications. The risk with large amount of volume in field stocks is that the accessibility for machines to operate on the forest site can change (ex. soft ground due to rainy weather), logs can 'disappear' (e.g. be over snowed) and the quality of logs can be degraded due to e.g. fungi and insects (Lindberg, 2016).

Achieving a balance in productivity between the machines while maintaining high and even utilization can be attained through careful scheduling of forest sites. Such scheduling might inlucde e.g. selection of stand features to compensate for differences in the machines' respecitve production rates, scheduling an additional machine when needed (e.g., one harvester and two forwarders), or improving harvest unit design (e.g., precences and locations of landings and roads) (Eriksson 2016). Such scheduling-related measures are normally used in regular operations, but there is still a need for flexibility to handle commonly occurring workflow variations (Johansson et al. 2022). The utilization and production rate of the machines are, of course, also affected by the amount of time they are staffed by machine operators. The staffing can be structured in many ways, from one person who operates many machines single-handedly (Kelly and Germain 2016) to many people who take turns to operate the same machine (Ager 2014). Expensive machines normally involve high fixed machine costs, which surges for a high usage to spread the fixed costs over more hours and more produced wood per year (Ager 2014; Eriksson 2016). However, labor regulations and operator requirements limit the hours during which machines can be operated. In the Swedish wood supply case, this has led to generally having two machine operators for each machine, each working full time (i.e. eight hours a day, five days a week) (Ager 2014; Eriksson 2016; Erlandsson, 2021). To allow flexibility in commonly occurring scenarios (Johansson et al. 2022), the operators can be asked to work less or more time. However, that possibility is not without challenges and limitations. In Sweden, for instance, labor regulations specify acceptable work time variations and how operators are compensated for such changes. It also restricts employees to operating the machines between certain hours during the night (Skogsavtalet 2020). Moreover, an existing labor shortage has meant that available operators are less tolerant of unpredictable and uncomfortable work conditions. The labor shortage also limits the possibilities to change machine usage by using temporary adjustments to the number of employed operators or by adjusting their working time (Johansson et al. 2021; Kronholm et al. 2019). Traditionally in the Nordic countries, the staffing of machines has mainly been driven by the cost-efficiency of the harvesting operations, as well as the well-being of the machine operators. However, how the machine or a machine group can be staffed and organized to reduce wood lead-time and what trade-offs it may have on the harvesting cost has only rarely been researched (i.e. Helstad et al. 2001). Therefore, the overall aim of this study was to evaluate trade-offs between the stump-to-road lead time of wood and harvesting cost by comparing harvester-forwarder groups staffed with different number of of full-time working operators, which thereby had different harvesting capacity and different flexibility in adjusting the field stock.

Materials and methods

Experimental design

The study considered a Nordic mechanized cut-to-length context and used discrete-event simulations (DES) to evaluate the production rate, resource utilization, field stock level as well as harvesting cost and lead-time per load (i.e. 20 m^3) from stump-to-roadside for different combinations of machine operators, initial field stock (see 2.2.1.1), and machine choice thresholds (see 2.2.2.1).

The trade-offs were evaluated by comparing harvesting groups that all consisted of one harvester and one forwarder, but which used 2, 3 or 4 machine operators working full-time. The scenarios reflected a common contractor in Sweden with a harvesting group consisting of one harvester and one forwarder with 2–4 machine operators in the crew (Kronholm et al. 2021). The groups operated over the same duration of calendar time and the study was designed to analyze how a machine group could be staffed in order to generate the most advantageous balance between lead time and harvesting cost. Stand condition-dependent time consumption and the occurrence of random downtime were included in the experiment. To isolate the effect of adapting machine use, stand selection was not used as a way of influencing field stock and harvesting capacity. In order to accommodate the variation in results in single simulation runs caused by the effect of differences in stand features, the order in which stands were harvested and the randomly occurring delays, all combinations were run using 50 different sets of forest stands.

Model building and simulations

General structure of the simulation model

AnyLogic 8 University 8.7.2 simulation software was used for the DES modelling. In DES, the item of interest passing through a system is called an entity. In this study, the entity was the equivalent of a full load of logs for a large-sized forwarder, which was set to 20 m^3. Time consumption for the harvester to fell and process one load and the forwarder to extract one load was calculated based on the stand-specific conditions, with all loads in a given stand having the same conditions. However, downtime was included in the model and added to the work time with random occurrences and durations.

In AnyLogic, the work of the harvester and forwarder was represented with one block each, which modeled the total time required for their respective work processes to finish the task of producing one full load. The simulation was set up according to the first-in-first-out principle, so that loads were handled according to the order in which they were introduced into the model. Loads that were harvested were represented by a queue block for the load to continue through the system i.e. waiting for the forwarder to pick up the load after it had been processed by the harvester. Hence, the quantity of harvested, but not yet extracted, loads changed every time a load was produced by the harvester or picked up by the forwarder. In this context, the *lead time* refers to the total time consumption for a load to go through the process of being harvested and extracted, including the "waiting time" (i.e. time in field stock) between machines.

A source block was used to generate the flow of loads that represented the harvesting work that began when the simulation was started. Loads were fed into the simulation according to the order of the stands in a spreadsheet. When the last load in a stand had been released to the harvester, the model went on to feed in the loads from the next stand in the spreadsheet. The time required for the respective machine to handle a specific load was predetermined in the model according to the stand-specific conditions (see 2.4.3 Time consumption), but its specific time of arrival in the model depended on the occurrence and effect of random downtime and the choice of which machines to operate (see below). There was no machine relocation time between the forest stands. The number of loads in a stand was also predetermined, and equal to the total volume divided by the volume of a load (i.e. 20 m^3) and then rounded up to the nearest integer.

The simulations were time-restricted to 205 production days. To facilitate the modeling, the days were allocated over 41 weeks with five production days and two production free days (i.e. weekends) per week. Hence, it did not consider the occurrence of individual or continuous days off due to holidays, sick leave, training days etc. or standstill periods during summer vacations that occur during a full year of 52 weeks.

The time restriction on the simulations resulted in not all stands available in the data being included in each simulation run. Moreover, the number of operators that staffed the machines determined the amount of work time per production day, which in turn resulted in different numbers of stands being included in the simulation runs.

At the end of each simulation, the resulting datasets were automatically recorded in new spreadsheets.

Initial field stock Three different initial field stock levels were used to represent different initial situations. The used initial field stock levels were 0, 68 and 119 loads. The field stock of 68 loads were set according to the personnel working for Stora Enso Skog AB assumptions for a field stock level that is large enough for efficient interactions between the machines, but small enough to reduce risks of complications with field stocks. The level of 119 loads was set to represent too high field stock, and the level of 0 loads was set to represent too low field stock. All loads in the initial field stock had the same stand-specific condition in all simulation runs. When a simulation started, the desired level of initial field stock between the machines was created by letting a specific source block generate loads directly to the forwarder. Hence, those loads went to the top of the forwarding queue as soon as the simulation started.

The operators' work and choice of machine to use

In the model, the harvesting and forwarding work required resources to be available. The resources were the machines and operators. Each workday was divided into two eight-hour work shifts, representing the usual way of working in Sweden. The work shifts were 6 am – 2 pm and 3 pm – 11 pm. The hour between the two shifts was created as a buffer between the operators to enable the modeling. The buffer hour enabled the handling of when partly finalized loads occurred at the end of a shift, thus allowing a little less or a little more time for each shift. To realize an average shift duration of 8 h, the final load could not be started when there was less than 25.5 min left of the shift for the harvester, and less than 28.5 min for the forwarder. Those time limits represented half of the average time consumption per load (in scheduled machine time) over all 87,110 loads from all 1550 forest stands in the stand dataset.

With 2 operators available, they worked one shift each, and both had therefore the option to choose which machine to operate and which to leave idle (Fig. 2). With 3 operators, two worked during the first shift and, hence, both the harvester and forwarder were used. The third operator worked the second shift, and could therefore choose machine. With 4 operators, two worked the first shift and two worked the second shift. This resulted in both harvester and forwarder working at their full capacity, but without any opportunity to purposly adjust the field stock. Hence, 100% of the work time was flexible and available for field stock adjustments with 2 operators. With 3 and 4 operators, 50% and 0%, respectively, of the work-shifts were flexible.

At the start of each shift, the available resources were allocated to work tasks in the model. Both machines were always available, but there might be a shortage of operators.

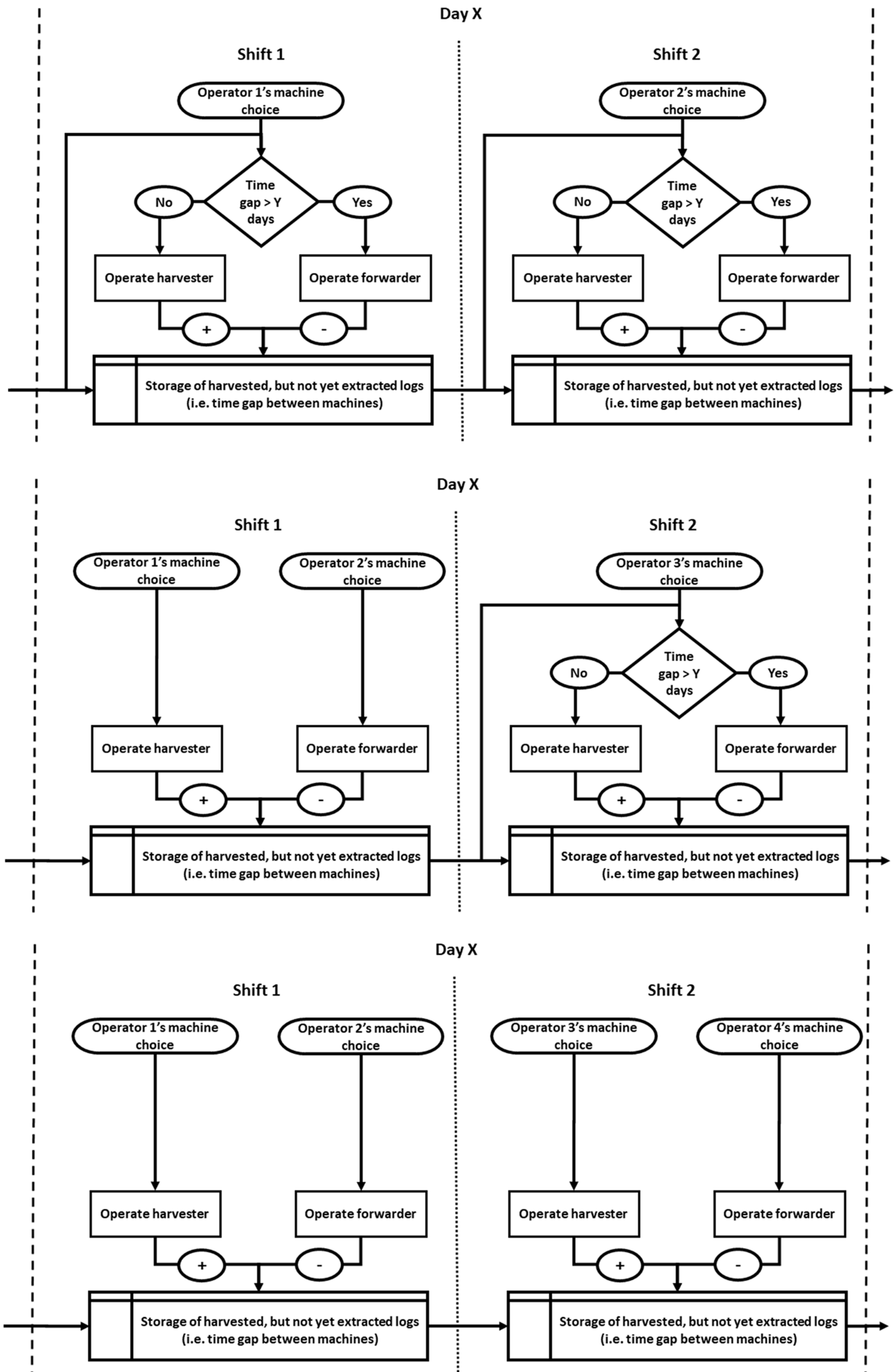


Fig. 2 Flow chart of the simulation model's structure for allocation of operators to machines, based on the machine choice threshold between the machines. Panel *(a)* shows allocation with 2 operators in the harvesting group. Panel *(b)* shows allocation with 3 operators in the harvesting group. Panel *(c)* shows allocation with 4 operators in the harvesting group

If there was a shortage (i.e. only 1 operator available), the operator was allocated for the whole shift to the machine with the highest priority at the start of the shift (Fig. 2). That meant that the other machine was idle during the whole shift. The prioritization depended on the predetermined productive work time for the forwarder to extract the field stock in the queue and the machine choice threshold.

Machine choice threshold In the model, a machine choice threshold was set to correspond to a time-gap between the machines. The time-gap between the machines represented the predetermined productive work time for the forwarder to extract the field stock in the queue. Thus, the time-gap varied depending on number of loads between the machines as well as the stand-specific conditions for the loads. When the time-gap between the machines was longer than the set machine choice threshold, the forwarder was prioritized in order to reduce the field stock (Fig. 2). When the time-gap was shorter than the machine choice threshold, the harvester was prioritized in order to increase the field stock. The three machine choice thresholds used in the experiment were 1, 4 and 7 full production days for the forwarder working in two shifts. Hence, in exact time, the thresholds were 14.24, 56.96 and 99.68 productive machine hours, respectively, with delays shorter than 15 min included (PMh_{15}). The levels used were selected with the same principle as for *initial field stock*, with a preferred time-gap between the machines (56.96 PMh_{15}), a too small (14.24 PMh_{15}), respective too long (99.68 PMh_{15}) according to personnel working at Stora Enso Skog AB.

Data

Forest stands

The stand dataset used in the simulation consisted of 1550 stands from final felling operations carried out between 1st of January and 31th of December 2021, collected from the forest company Stora Enso Skog AB. The data contained information on harvested volumes as well as on tree and terrain features (Table 1). These variables were used to calculate the stand-specific time consumption for the harvesting and forwarding of the loads in the stand, as well as the number of loads in each stand (see 2.3). The dataset originated from a larger dataset which had been filtered in order to exclude stands with obvious inaccuracies. This was achieved using a simple algorithm for reducing frequencies of outliers, based on value thresholds agreed upon with experienced forest company representatives. The outlier reduction algorithm was designed to remove obvious errors from the data, while allowing cases that could potentially be erroneous but might be unusual observations that had been correctly recorded. Stands were considered as outliers if the associated data was < Min or > Max, as shown in Table 1. This resulted in the exclusion of 6.2% of the forest stands from the original dataset, which accounted for 3.0% of the harvested volume.

Table 1 Summary statistics for the stands used in the study. $N = 1550$ forest stands

Variable	Unit/Class	Mean	StDev	Min	Max
Mean stem size	m^3	0.37	0.15	0.05	1.00
Mean extraction distance	meters	346	219	50	1300
Total volume	m^3	1124	1164	18	12,059
Volume per hectare	m^3/ha	242	104	7	930
Terrain roughness	1–5	2	1	1	5
Slope	1–5	2	1	1	5
Assortments	n	7	1	1	17

Note Volumes are for logs, in solid m^3 under bark

Each simulation run was executed in a randomly arranged order of the forest stands in the dataset. The same forest stand order was used for all combinations of factors and their levels. Hence, in a given simulation run (e.g. simulation run 1), all 27 factor combinations used the same forest stand data.

Time consumption and downtime

Time consumption for the machine work was the basis for deriving lead times as well as costs. Final felling productivity models from Eriksson and Lindroos (2014) were used to calculate time consumption for harvesting (model *v*) and forwarding (model *iv*). Those models required information about the forest stand, for instance mean stem size and extraction distance, which was provided from the dataset of forest stands (Table 1). The models also required information about undergrowth and difficult trees, which was not included in the dataset. However, as part of the forest company's normal routine, forest stands with obstructing undergrowth were cleaned prior to the harvesting operation. It was, therefore, assumed that the stands had no or just small amounts of undergrowth, so the undergrowth value of 100 trees/ha was used for all stands. For difficult trees, the mean value of Eriksson & Lindroos' (2014) dataset was used (3.02%).

The PMh_0 time in Eriksson and Lindroos (2014) was converted to PMh_{15} by using the conversion rates 0.88 and 0.93 PMh_0/PMh_{15} for harvester and forwarder, respectively. These conversion rates could be derived from data for 48% of the harvesters and 70% of the forwarders within the detailed follow-up dataset described below. Hence, the productivities provided using PMh_0 by the models from Eriksson and Lindroos (2014) were decreased by multiplying by 0.88 for the harvester and 0.93 for the forwarder.

Downtime occur when a system is unavailable, and is often also referred to as a delay. It was included in the model, with occurrences and durations being governed by probability density functions. The functions were derived from a detailed follow-up data for 23 harvesters and 33 forwarders provided by Stora Enso Skog AB. The follow-up data originated from machines that had operated for at least 100 productive machine hours (PMh_{15}) between January and December 2021. Time recorded as downtime included maintenance, repairs, and interruptions such as recoveries, waiting for relocation, demonstration to visitors etc.

Scheduled breaks/meals and relocations were not included in downtime. The average downtime in the simulation was compared and calibrated using the follow-up data for machine utilization rates. This was possible since the follow-up data, apart from downtime, also contained productive machine time including downtimes shorter than 15 min (PMh_{15}). The average utilization rate in the follow-up data was 86% for harvesters and 89% for forwarders. The probability density function (PDF) for downtime occurrence for the harvester was derived and set to a negative exponential function with a shift parameter of 0, a scale parameter of 300 and truncation at 2 and 3840 min. The PDF for the length of each downtime was also derived and set to a negative exponential function with a shift 0, scale 25, and truncation at 15 and 1100 min. Corresponding PDFs for the forwarder were also negative exponential functions. The occurrence PDF parameters were a shift 0, scale 380 and truncation at 2 and 3840 min, whereas the length PDF parameters were a shift 0, scale 20, and truncation at 15 and 650 min (Table 2).

Cost

For cost calculations, estimations of cost components for large-sized machines were provided by the forest company according to their costing model. Costs were aggregations of fixed machine costs, variable machine costs and operator costs (Table 3). The fixed machine cost consisted of investment, insurance, and other costs (i.e. business management costs), while variable machine costs consisted of fuel consumption and maintenance. In the study, fixed machine costs were allocated to the machines each production day, whereas variable machine costs and operator costs were

Table 2 Application of probability density functions and their parameters in the simulations

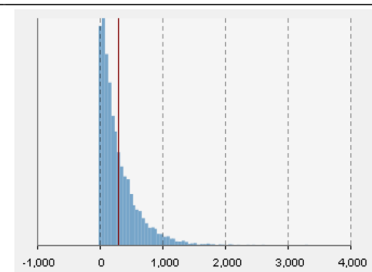
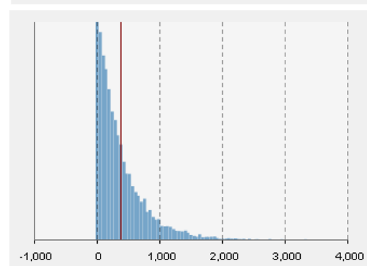
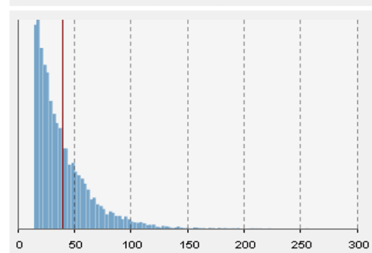
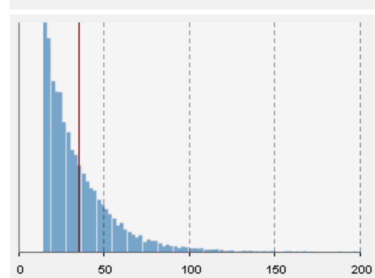
Application	Machine	Function	Parameters	Truncation	Visualization
Downtime occurance (minutes)	Harvester	Exponental distribution	Mean (scale) = 300, shift (threshold) = 0	min = 2, max = 3840	
Downtime occurance (minutes)	Forwarder	Exponental distribution	Mean (scale) = 380, shift (threshold) = 0	min = 2, max = 3840	
Downtime duration (minutes)	Harvester	Exponental distribution	Mean (scale) = 25, shift (threshold) = 0	min = 15, max = 1100	
Downtime duration (minutes)	Forwarder	Exponental distribution	Mean (scale) = 20, shift (threshold) = 0	min = 15, max = 650	

Table 3 Cost estimations used in the simulations

		Machine operators in the harvesting group		
Type of cost	Cost unit	2	3	4
Fixed harvester cost	$/production day[a]	359.0	415.0	502.0
Fixed forwarder cost	$/production day[a]	296.0	344.0	419.0
Variable harvester cost	$/SMh[b]	48.6	48.6	48.6
Variable forwarder cost	$/SMh[c]	41.8	41.8	41.8
Operator cost	$/SMh[b, c]	43.5	43.5	43.5

[a].Calculated on the basis of 205 production days per year, and with less work time per day with fewer operators (i.e. 8, 12 and 16 h per machine and production day with 2, 3 and 4 operators respectively). The production days exclude weekends, holidays, sick leave, training days etc. [b]. Including downtime for harvester (Cost for $PMH_{15} \times 0.86$). [c]. Including downtime for forwarder (Cost for $PMH_{15} \times 0.89$)

only applied to a machine when it was used. Hence, when a machine was idle, there were only fixed machine costs. Operator cost was the same for both the harvester and the forwarder.

In the costing model, the utilization rates were set according to the follow-up dataset, using 86% for harvester and 89% for forwarder. To accommodate the differences in annual machine usage with the different number of operators, the expected lifetime was set as 9.0, 6.1, and 4.6 years for 2, 3 and 4 operators respectively. Similarly, the salvage value was set to 15%, 22.5% and 30% of machine investments for respective operator alternative. These values were based on estimations from personnel working for Stora Enso Skog AB.

Output and analysis

The outputs consisted of the weekly numbers of loads produced by each machine, the number of shifts that the operators worked with each machine, the harvester forwarder utilizations, the field stock levels in number of loads, lead time per load, harvesting cost per load, forwarding cost per load and total cost per load.

The mean number of shifts was calculated by summing all shifts per week and dividing by 41 weeks of work time per year (when deducing vacation, holidays, sick leaves and other free days (see 2.3.1)).

The machine utilizations were calculated based on a maximum weekly availability of 80 SMh, irrespective of the number of operators in the system. Hence, the PMh_{15}-time recorded for each week was divided by 80 and then multiplied by 100 to obtain the utilization rate in percent. The total machine utilization for the whole simulation was correspondingly calculated but by summing all productive work time and dividing by 3280 SMh per year (80 SMh/week × 41 weeks).

The field stock levels were measured weekly, using statistical analysis in AnyLogic for continuous recording to derive the mean value for the field stock each week. The mean field stock level was calculated by summing all mean field stock levels per week and dividing by 41 weeks.

The lead time was registered for each finished load delivered to roadside, and the mean lead time was reported at the end of the simulation given the lead times of the loads and number of loads.

The harvesting and forwarding costs per load were reported at the end of the simulation. The costs were measured in the model according to the fixed machine cost added with the machine variable cost and operator cost. The machine variable cost and operator cost depended on the machine's utilization and number of shifts in which the operators had used the machine. The mean cost per load was then derived by dividing the sum of the machine fixed cost, variable cost, and operator cost by the produced number of loads. Information about the cost components used is provided in Sect. 2.4.4 Cost and Table 3.

These results were analyzed and compared between the different combinations of machine operators, machine choice thresholds and initial field stocks using Minitab 18.

Results

The results are presented in sections focusing on individual aspects of the operations: production rate, resource utilization, field stock level as well as cost and lead-time per load. Subsequently, the trade-offs between lead time and harvesting cost compared for the different combinations of machine operators, machine choice thresholds and initial field stock.

Production rate

The production rate was, as expected, proportional to the number of operators. On average, for both machines in the system, each operator contributed 45 loads per week, irrespective of number of operators in the system. However, how the loads were allocated on the machines differed. With 4 operators, there was no possibility for flexibility in terms of influencing the machine's production rate, which showed that the harvester is 12% faster than the forwarder in the studied stand conditions. With 2 and 3 operators, the flexibility and machine choice thresholds resulted in evenly distributed production rates for both machines. The different machine choice thresholds as well as different initial field stocks had small (< 3 loads per week), but yet distinct, effects on the average distribution of production between machines within a system with 2 or 3 operators. A low threshold resulted in a lower production rate for the harvester and a higher rate for the forwarder, compared with a high threshold. For initial field stock, a low field stock resulted in a higher production rate for the harvester and a lower one for the forwarder, compared with a high initial field stock (Fig. 3). With 4 operators, the lack of possible flexibility in production rates resulted in equal production rates irrespective of machine choice threshold and initial field stock levels. The small observed differences reflect the randomly occurring downtimes in the simulations. The variation in mean weekly production rates between simulation runs was lowest with 2 operators, irrespective of machine, levels of threshold and initial field stock (Fig. 3). For the harvester, the highest number of operators had the highest variation in mean weekly production rates, whereas the variation for the forwarder was rather similar for both 3 and 4 operators.

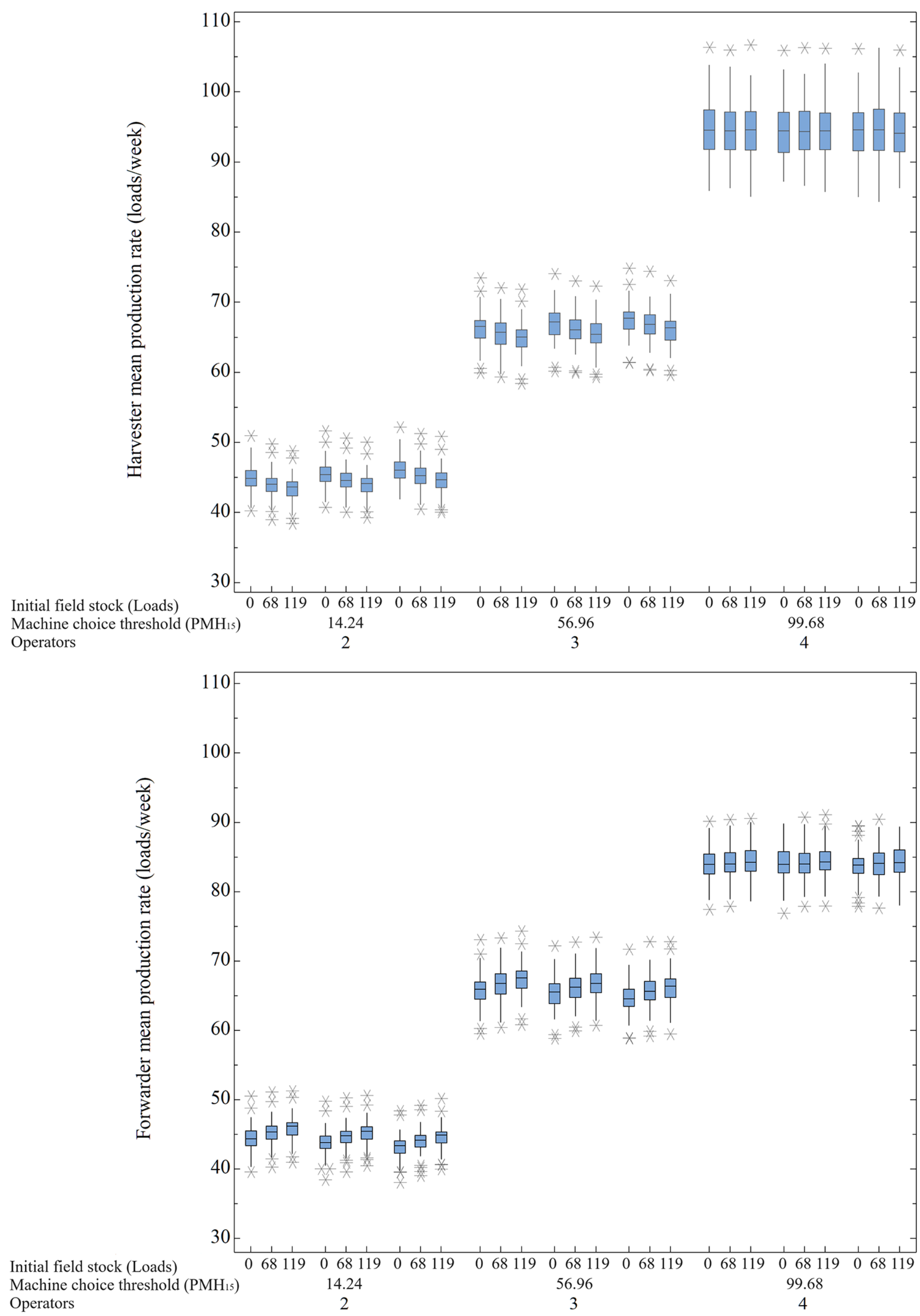


Fig. 3 Mean production rates for the harvester (above) and the forwarder (below) for all combination of operators, machine choice threshold and initial field stock. Box edges are the first and third quartiles, whereas the horizontal line in the box denotes the median. Whiskers are extended to observations within ±1.5×Interquartile Range from the box edges, and stars are observations exceeding the whiskers. $n=50$ sets of forest stands

Machine resource utilization

With 2 operators, the ten available shifts per week were, on average, slightly more allocated to the forwarder (mean values ranged between 4.3 and 5.0 shifts for the harvester and 5.0–5.7 shifts for the forwarder). Also, with 3 operators, the 15 available shifts per week were, to a larger extent, allocated to the forwarder (mean values ranged from 6.7 to 7.4 shifts for the harvester and 7.6–8.3 shifts for the forwarder). There was a small, but clear tendency to allocate more shifts to the harvester with a lower initial field stock and higher machine choice threshold. With 4 operators, the 20 available shifts per week were evenly allocated to both machines due to the lack of possibility to adjust, with no effects from initial field stock or machine choice threshold.

The mean utilization of the available machine time mirrored well the mean utilization rates, with almost twice as high values with 4 operators compared with 2 operators. For the harvester, the mean utilization rates with 4, 3, and 2 operators ranged between 84.2–87.4%, 56.6–63.8%, and 36.5–43.5%, respectively. The corresponding ranges for the forwarder were 88.1–90.7%, 67.2–74.0%, and 44.0–50.8%. As with the distribution of shifts between machines, there was a small, but clear tendency of higher utilization of the harvester with a lower initial field stock and higher machine choice threshold.

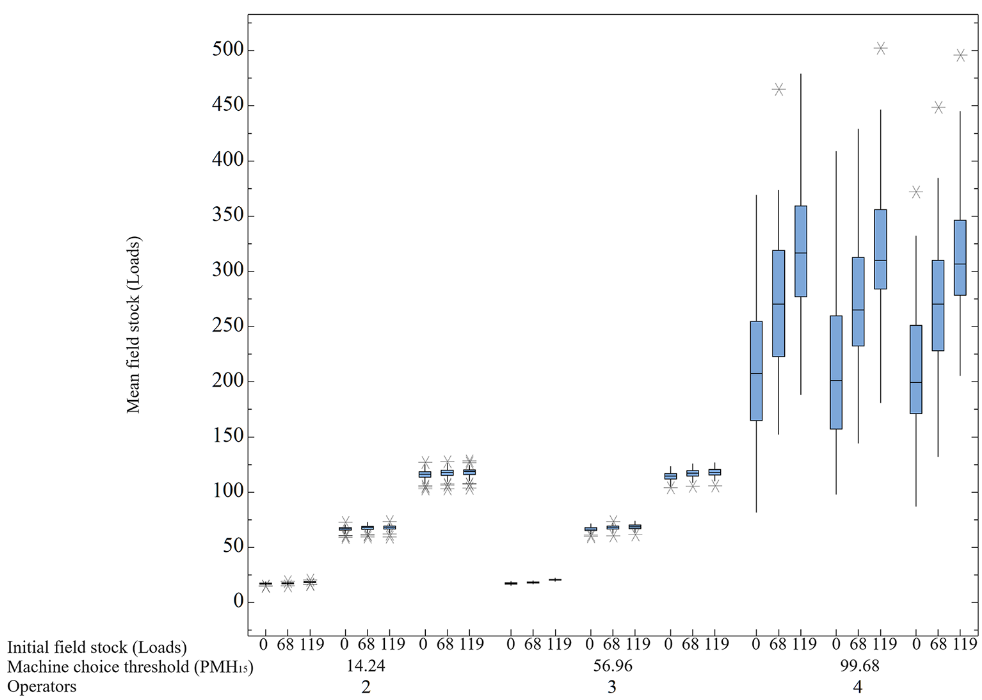
Field stock between machines

The average levels of mean field stock in number of loads between the machines differed greatly between number of operators on the system, both in terms of levels and the variation between simulation runs (Fig. 4). With 2 and 3 operators, there was very little variation in mean field stock, whereas the variation was considerable with 4 operators. Other differences were the positive correlations between the machine choice threshold and mean field stock for 2 and 3 operators, but lack of such correlations with 4 operators. For both 2 and 3 operators, the average field stock was 17, 67, and 117 loads with machine choice thresholds of 1, 4, and 7 production days, respectively. On the other hand, with four operators, the initial field stock had a distinct effect, with the effect having similar magnitudes to the initial field stock itself. With 4 operators, the average field stock level was 212, 272, and 319 loads with initial field stock levels of 0, 68, and 119 loads, respectively. With 2 and 3 operators, the effect was considerably smaller, if noticeable at all.

Lead time per load

The rather small difference in field stock with 2 and 3 operators was amplified to rather large differences when expressed as lead time, due to differences in available work time per day. Hence, the average levels of mean lead time over the weeks in each simulation run differed greatly between number of operators, both in terms of average levels and the variation between simulation runs (Fig. 5). The longest lead times and the largest variations between simulation runs occurred with 4 operators (Fig. 5), when there was no flexibility in flow management. With 2 and 3 operators, the lead time was positively correlated with the machine choice threshold (Fig. 5), with smaller threshold levels resulting in

Fig. 4 Mean field stock for all combinations of operators, machine choice threshold and initial field stock. Box edges are the first and third quartiles, whereas the horizontal line in the box denotes the median. Whiskers are extended to observations within ±1.5×Interquartile Range from the box edges, and stars are observations exceeding the whiskers. $n = 50$ sets of forest stands



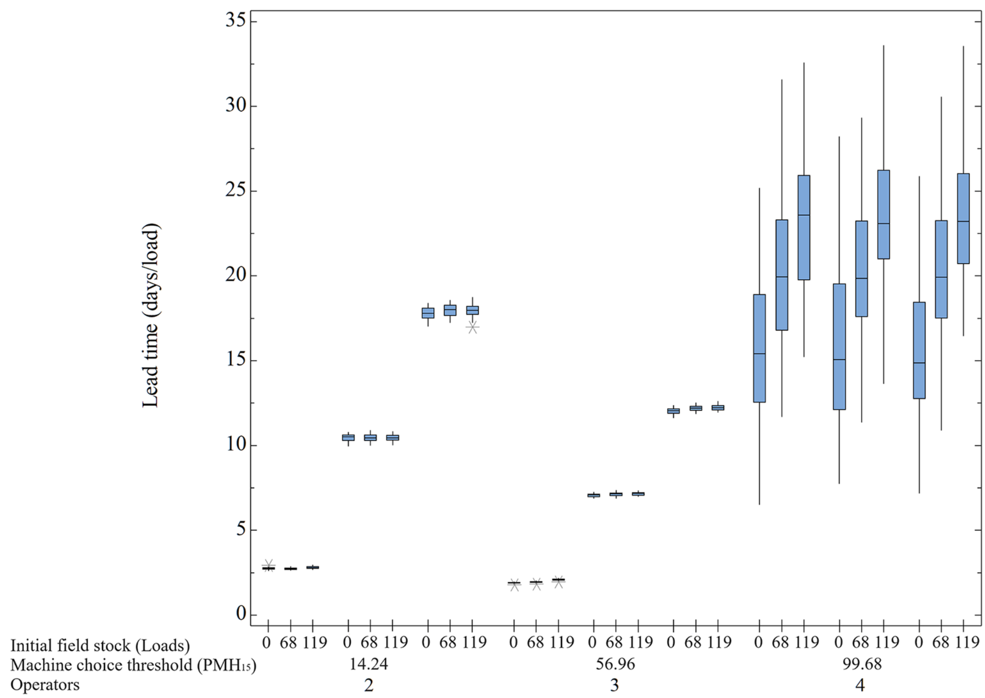


Fig. 5 Mean lead time for the loads to be felled and extracted to roadside for all combinations of operators, machine choice threshold and initial field stock. Box edges are the first and third quartiles, whereas the horizontal line in the box denotes the median. Whiskers are extended to observations within $\pm 1.5\times$Interquartile Range from the box edges, and stars are observations exceeding the whiskers. $n=50$ sets of forest stands

shorter lead times. The lead times were shortest with 3 operators. With both 2 and 3 operators, the variation in mean lead time was very small between simulation runs, and it was slightly smaller for 3 rather than 2 operators. With 4 operators, the initial field stock had a distinct effect, with the effect being of the same magnitude as the length of the initial initial field stock. With 2 and 3 operators, the effect was considerably smaller, if noticeable at all.

Cost per load

The cost was proportional to the production and resource utilization (Fig. 3). The higher production and resource utilization, the lower the harvesting cost. Hence, the cost for the harvester and the forwarder (Fig. 6), as well as total cost (Fig. 7), was lowest with 4 operators, and highest with 2 operators. With 2 and 3 operators, a low machine choice threshold resulted in a higher cost for the harvester and a lower cost for the forwarder, compared with a high threshold. A low initial field stock resulted in a lower cost for the harvester and a higher cost for the forwarder, compared with a high initial field stock (Fig. 6). The differences in the respective machine costs evened out, so the total cost with 2 and 3 operators was equal over levels of initial field stock and machine choice threshold (Fig. 7). With four operators, there were no effects of initial field stock or machine choice threshold on the cost for the harvester or the forwarder, and thus on the total cost.

Trade-offs between lead time and harvesting cost

With 4 operators, there was a negative relationship between costs and lead time. However, both costs and lead times varied substantially between simulation runs, indicating the effects of stand order. For 2 and 3 operators, there were large variations in costs between simulation runs but virtually no variation in lead time. On average, the costs were lowest with 4 operators, and the lead time was shortest with 3 operators. However, there were substantial overlaps in costs between all numbers of operators, and in lead time for some combinations of machine choice thresholds and initial field stock levels. The differences in lead time between 2 and 3 operators were substantially influenced by machine choice threshold levels, whereas the initial field stock influenced the lead time for 4 operators. The costs were not influenced to the same extent.

The trade-off effects were present for all combinations of machine choice threshold and initial field stock levels, but the magnitude of the effect varied. With the combination of the lowest machine choice threshold and medium initial field stock, it was possible with 3 operators to keep the lead time, on average, 90% lower than with 4 operators at an expense of 3.4% higher costs (Table 4). With the high machine choice threshold and medium initial field stock levels, the effects were similar but the difference in lead times were substantially lower. Three operators outperformed 2 operators in both average lead time and costs for all combinations of machine choice thresholds and initial field stock levels (Fig. 8; Table 4).

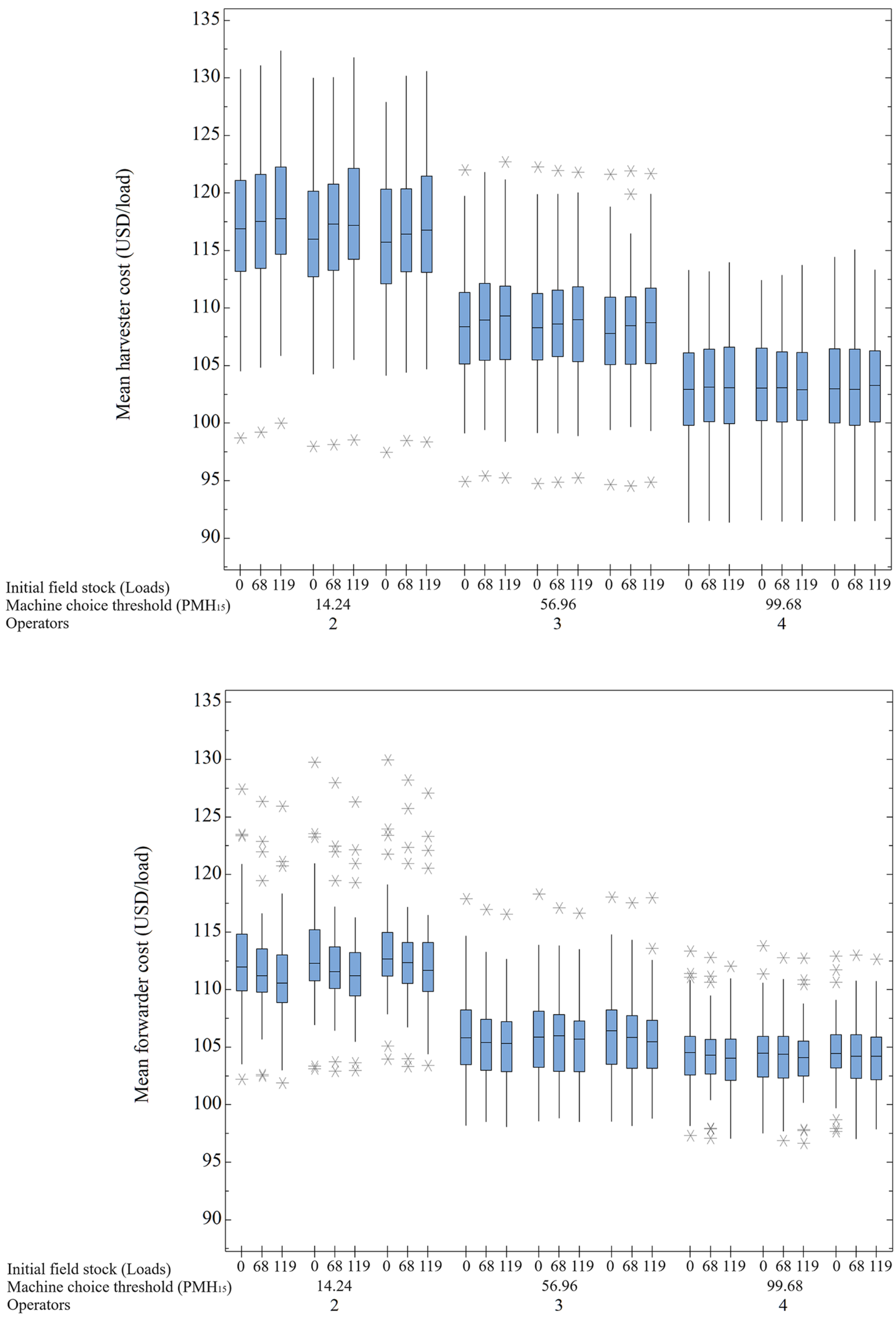


Fig. 6 Mean harvester (above) and forwarder (below) cost per load for all combination of operators, machine choice threshold and initial field stock. Box edges are the first and third quartiles, whereas the horizontal line in the box denotes the median. Whiskers are extended to observations within ± 1.5×Interquartile Range from the box edges, and stars are observations exceeding the whiskers. $n = 50$ sets of forest stands

Discussion

This study evaluated trade-offs between lead time and harvesting cost, by comparing harvesting groups staffed with different number of full-time working operators and thereby being differently flexible in adjusting the field stock. These findings have a potential to improve decisions relating to how field stock and harvesting capacity can be balanced to meet specific objectives.

There was a distinct order in how well balanced the lead time and harvesting cost was between the different numbers of operators. With 2 operators, 100% of the work time was available for adjusting the field stock but at the expense of one machine always standing idle. This high amount of flexibility was a suboptimal solution, that both generated high

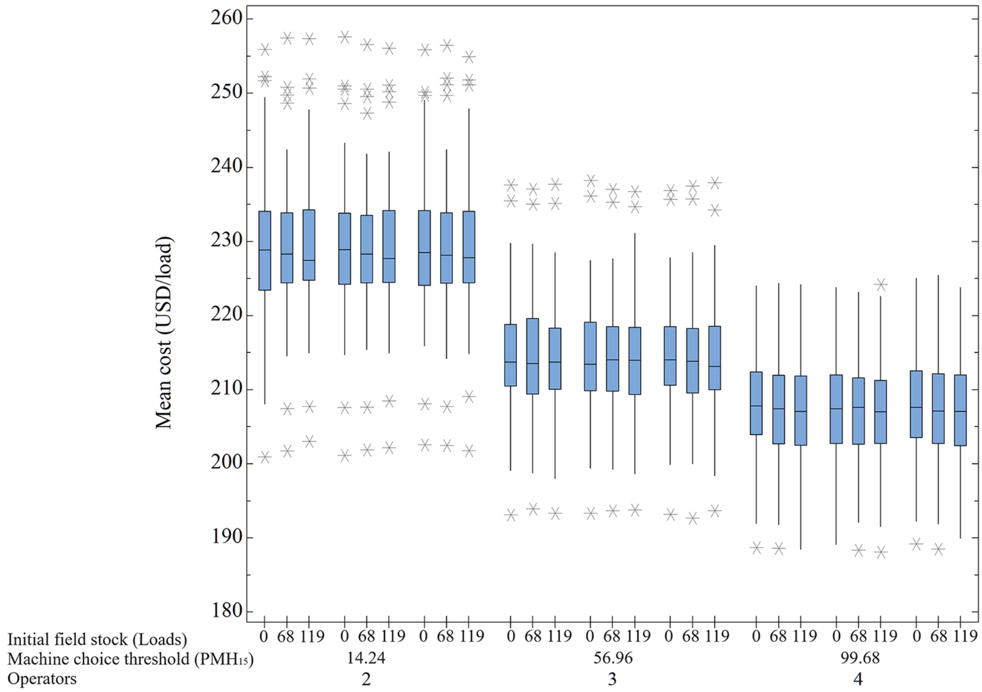


Fig. 7 Total mean cost per load for all combinations of operators, machine choice threshold and initial field stock. Box edges are the first and third quartiles, whereas the horizontal line in the box denotes the median. Whiskers are extended to observations within ± 1.5×Interquartile Range from the box edges, and stars are observations exceeding the whiskers. $n = 50$ sets of forest stands

Table 4 Lead time and harvesting cost with 2 and 3 operators in relation to using 4 operators. Values are expressed as percentage of the values for 4 operators (e.g. (value for 2 operators - value for 4 operators)/value for 4 operators)) x 100)

Operators	Efficiency type	Low machine choice threshold			Medium machine choice threshold			High machine choice threshold		
		Low initial field stock	Medium initial field stock	High initial field stock	Low initial field stock	Medium initial field stock	High initial field stock	Low initial field stock	Medium initial field stock	High initial field stock
2	Lead time	-82	-86	-88	-33	-48	-55	14	-10	-23
	Cost	10.4	10.6	10.6	10.5	10.5	10.6	10.4	10.5	10.5
3	Lead time	-88	-90	-91	-55	-64	-69	-22	-39	-48
	Cost	3.3	3.4	3.4	3.3	3.3	3.4	3.2	3.2	3.3

costs and not the best lead times. Of the options tested in the study, the flexibility achieved with 3 operators was the most advantageous alternative. It generated the shortest lead times and compared to 4 operators, the lead times were on average 22–91% faster with 3 operators. That for an average trade-off of 3.4% higher cost than the staffing option with lowest harvesting cost (4 operators). However, it should be noted that the costs differed greatly between the simulations runs, for all number of operators used.

In order to accommodate the variation in working conditions introduced by the order of forest stands in the simulation runs, the simulations were run using 50 different orderings of the stands. With 4 operators, the results from individual simulation runs differed greatly in production rate (Fig. 3), field stock (Fig. 4), lead times (Fig. 5) and costs (Figs. 6 and 7). Nevertheless, the resource utilization was stable over the different simulation runs and differed by less than 3.2%. These effects were expected, since 4 operators was the staffing option in which both machines were used to their full capacity and there was no flexibility to adjust the field stock by adapting the machine usage. Hence, differences in stand conditions between simulations were expected to result in the observed variations.

With 2 and 3 operators, flexibility was possible in terms of the potential to choose which machine to operate in order to adjust the field stock. Also, for these staffing options, there were variations in production rates and costs between different simulation runs, but with minimal variation in field stock or in lead times (Figs. 4 and 5). Hence, the created flexibility allowed handling of the work condition variations (i.e. different stand orders) in terms of maintaining sufficient field stock level. These findings indicate that it should be possible to combine the production rate management using agile stand selection as suggested by Eriksson (2016), with the flexibility in which machine to operate studied here. It is likely that such a combination could provide a better balance between lead time and harvesting cost than found in this study. However, it is likely to require exploration of how machine choice threshold levels etc. should be adapted to, and adjusted for, the stand selection process. Often, stand

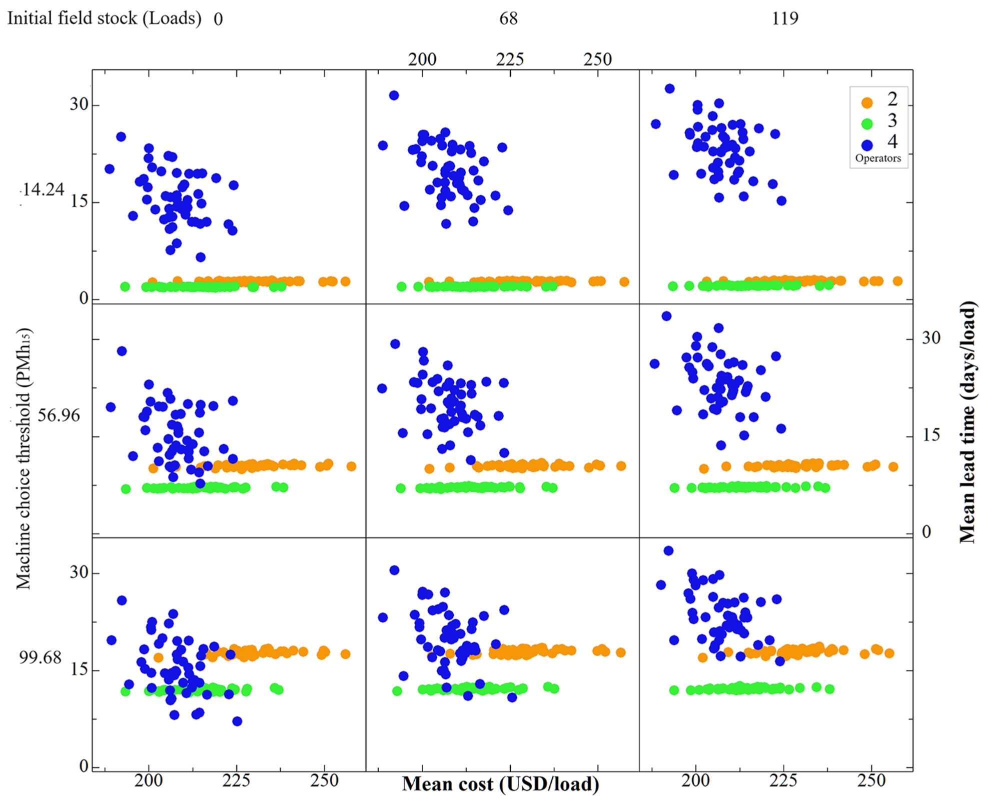


Fig. 8 Mean lead time plotted against mean cost per load for all combination of operators, machine choice thresholds and initial field stock. $n = 50$ sets of forest stands

selection is substantially constrained by, for instance, the limited number of available forest stands to harvest, forest management plans, assortment demands, and is subjected to a high level of unpredictability (weather, data quality, operator differences, resource availability etc.) (Gautam et al. 2013; Häggström and Lindroos 2016; Gustafsson, 2017). As stated by Audy et al. (2012), the uncertainties and feasibility for harvesting operations and stock holdings differ over a given year. Therefore, it is likely that also the importance of field stock levels in harvesting operations differs over time, due to weather seasons and other cyclic events. This calls for a dynamic balance of field stock and harvesting capacity, which may potentially improve the total balance. It is, therefore, easy to see that more research is needed into the potentials and limitations of both flexible machine choice and agile stand selection to explore how they, both separately and combined, can be used to reduce lead time and harvesting cost. Naturally, there are also other ways to create capacity flexibility that would be relevant to investigate, such as if there were flexibility not only within individual pairs of machines, but also between several pairs of machines.

In this study, the harvester had 12% higher production rate than the forwarder. Such a relationship is commonly encountered in final fellings in Sweden (Eriksson and Lindroos 2014), and it is likely to be one of the reasons for uneven working time on and volume production of machines (Johansson et al. 2022). Due to the high variability and unpredictability in harvesting operations, it is unlikely that it will be possible to arrange work environments in which the machines' production will match perfectly. Hence, there is a need for flexibility between the machine types. Such flexibility is already created, for instance by contractors who adapt the usage of their different machines (Johansson et al. 2022). The simulations in this study revealed large potentials to reduce field stock and reduce lead time when having flexibility between the machines (Figs. 4 and 5). Therefore, both shorter and more predictable lead times can be achieved if the machine group is staffed to enable machine resource utilization to vary according to desired field stock. In that way, the field stock and lead time is substantially less dependent on how contractors manage to create flexibility in a set-up not specifically designed for it, or how the forest company manage to provide flexibility by agile stand selection.

With 2 and 3 operators, the mean field stock depended on the machine choice threshold, while initial field stock was less important. For 4 operators, the initial field stock was maintained throughout the simulation. This indicates that the flexibility created by staffing generated a robustness that managed to handle challenges with initial field stock introduced in the simulations. The results also revealed that the lead time could be improved by on average 90% when having flexibility compared to not having it, with low machine choice threshold and medium (68 loads) initial field stock (Fig. 8; Table 4). The difference was higher with a high initial field stock and low machine choice threshold. With the low machine choice threshold, the average field stock was 18 loads. So, it was possible to have an average field stock level that might be so low that its use was questionable. A low field stock means low buffer possibilities, which are associated with increased risks of production delays (Puchkova et al. 2015). Therefore, it is not clear that the lowest field stock gives the best balance between lead time and harvesting cost overall. More research is needed into the most suitable field stock level.

Without capacity flexibility in harvesting operation, large field stocks occurred between the harvester and forwarder. Moreover, it resulted in long lead times for the wood to go through the two-machine system. A large field stock increases the risk that accessibility for machines to operate on the forest site changes while logs are in field storage, that logs disappear (ex. over snowed logs) and that their quality degrade (Lindberg, 2016). Therefore, even if the machines are staffed to be used at their full potential, their utilization will still need to be adjusted. This adjustment of utilization of the machines will also mean a capacity flexibility that will, most likely, increase the level and the uncertainties of costs. Both the machine and operator may then need to be idle while waiting for the other machine to catch up. It can also cause a need for machine operators to operate outside normal working hours to catch up with the production using the machine that falls behind. However, working outside normal working hours is not without challenges and limitations such as labor requirements and opportunities to rapidly adjust number of machine operators (Skogsavtalet 2020; Johansson et al. 2021; Kronholm et al. 2021). This study did not include any further investigations into the challenges and potentials for machine operators working outside normal working time or temporary employed operators etc. Hence, the results for 4 operators are likely to be underestimated in costs and overestimated in lead times if the changes required to adapt the work to limitations in acceptable field stock levels had also been considered.

It is difficult to forecast whether an increased focus on field stock and lead time from stump-to-roadside will facilitate the management of the challenging wood supply problem (Gautam et al. 2013). In fact, it might make the challenging problem even more complicated to handle and solve. However, it would be an approach that better mirrors reality, since field stock and lead time is an essential part of the daily work of forest operations managers, despite its limited research results.

Strengths and weaknesses

The advantage of using a simulation model is that it can mimic a specific bounded real system in a robust way, and the effects of different kinds of manipulation of a system can be evaluated without carrying out expensive or hazardous physical experiments (Banks et al. 2005). In the model within this study, different staffing of the standard two-machine cut-to-length harvesting system could be evaluated under controlled and comparable conditions. This is something that is difficult to do with a physical experiment, as such a study would be extensive and expensive. Moreover, it would also be impossible to compare the combination of factors under identical conditions. Therefore, the simulations in this study were valuable for exploring the effects of different staffing. However, as with all models, simplifications of the reality and system boundaries have been made.

In the simulations, forest stands, as well as the occurrence of downtime, caused variations in investigated outputs. However, it should be mentioned that the study has not accounted for many other variations that, in a real operation, would affect the outcome of the flexibility adaptions used in the model as well as the results. For instance, different operator skills have not been accounted for, neither how operators might work in the simulated flexible way. For instance, the machines may be in different locations, far from each other, and operators might not be capable of operating both machine types equally well or at all. However, the model has some features to accommodate for realistic conditions, for example, by not allowing machine operators to change machines during the shift.

The time required for relocation of machines and equipment between forest stands was not included. According to Eriksson and Lindroos (2014), relocations represent 1.5% and 0.9% of the total scheduled working time for a harvester and forwarder, respectively. Therefore, the production rates are a little overestimated and costs underestimated, but it should influence all combinations of factors similarly. Moreover, the model did not include sick leave, vacations, training days etc. for the operators. Therefore, the model was run over 41 weeks which represented one year of production days. The simulation model yielded, in that way, realistic annual values, and values relevant for the comparisons in the study. However, due to the "compressed work year", the weekly production rate can be expected to be overestimated, whereas the weekly variation and the lead times were underestimated.

When focusing on a single operation within the supply chain as this study did, it does not show how different adaptions propagates throughout the rest of the supply chain. Neither does it tell where in the chain, it is most efficient to gain lead time with minimized negative effects on other factors that may affect the end customer value and satisfaction. Thus, albeit that the study clearly indicates the potential and possibility of forest operations to trade harvesting cost for improved lead time, it is not able to show if, and how much, should be done when considering the whole supply chain. However, the study indicates that the rather unexplored focus on lead time in the initial part of the supply chain migh prove to be a valuable addition to other already used measures to manage wood flow.

Conclusions

This theoretical study evaluated trade-offs between lead time and harvesting cost, when handling the challenge to balance the interactions between harvesting and forwarding in Nordic mechaniced CTL-operations. It both showed the need for flexibility, and how it could be done by staffing a harvester and forwarder group with different number of full-time working operators. Different staffing meant different amount of capacity to adjust field stock level at the expense of harvesting capacity. To staff the machines with 4 operators was, in the study, related to no adjustability, and provided the lowest harvesting cost but long and highly variable lead time from stump-to-roadside. To staff the machine with 2 operators resulted in complete adjustability, but at the expense of higher harvesting cost and relatively long lead time. The best balance was achieved when staffing the machines with 3 operators, and thereby allocating 50% of the used work-shifts to adjustment of the field stock level. This resulted in the shortest lead times and the smallest cost increase. Compared to 4 operators, the lead times were on average 22–91% faster with 3 operators, depending on initial field stock and machine choice thresholds, but it came with cost increases of on average 3.2–3.4%. Hence, the results indicate that it should be possible to decrease lead time substantially with rather small cost increases. Future research should further explore how the focus on operator flexibility can be created and managed for improving the balancing that operations managers currently carry out with mainly other measures.

Author contributions M.J conceived the original idea. All authors was involved in designing the study and choice of method. M.J and M.L did the model development and simulations. M.J wrote the main manuscript text and O.L prepared Fig. 2. M.J did the analysis with input from M.L and O.L. All authors reviewed the manuscript.

Funding This study was a part of Johansson's industrial doctoral project, which was financed by Stora Enso AB.
Open access funding provided by Swedish University of Agricultural Sciences.

Data availability Contact the corresponding author for access to data on reasonable request.

Code availability Contact the corresponding author for access to codes generated for the data analysis for the study on reasonable request.

Declarations

Conflict of interest The author declares that they have no competing of interest.

References

Ager B (2014) Skogsarbetets humanisering och rationalisering från 1900 och framåt, Doctoral dissertation, Luleå tekniska universitet, [In Swedish]

Audy JF, Moreira MP, Westlund K, D'Amours S, LeBel L, Rönnqvist M (2012) Alternative logistics concepts fitting different wood supply situations and markets. CIRRELT

Banks J, Carson J, Nelson B, Nicol D (2005) Discrete-Event System Simulation: Pearson Education India

Bredström D, Lundgren JT, Rönnqvist M, Carlsson D, Mason A (2004) Supply chain optimization in the pulp mill industry–IP models,column generation and novel constraint branches. Eur J Oper Res 156:2–22

Carlsson D, Rönnqvist M (2005) Supply chain management in forestry—case studies at Södra Cell AB. Eur J Oper Res 163(3):589–616

Eliasson L (2022) Fördjupad analys av skogsbrukets kostnader och intäkter. Arbetsrapport 1124–2022. SkogForsk, Uppsala, Sweden. [In Swedish]

Eriksson M (2016) Developing client-supplier alignment in Swedish wood supply Doctoral thesis. Acta Universitatis agriculturae Sueciae, 2016:32

Eriksson M, Lindroos O (2014) Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. Int J Eng 25(3):179–200

Gautam S, LeBel L, Beaudoin D (2013) Agility capabilities in wood procurement systems: a literature synthesis. Int J for Eng 24(3):216–232

Gustafsson Å (2017) Assessing work order information quality in harvesting. Silva Fennica 51(4):1–18

Haartveit EY, Fjeld DE (2003) Simulating effects of supply chain configuration on industrial dynamics in the forest sector. Int J for Eng 14(2):21–30

Häggström C, Lindroos O (2016) Human, technology, organization and environment–a human factors perspective on performance in forest harvesting. Int J for Eng 27(2):67–78

Hansen E, Juslin H (2018) Strategic marketing in the global forest industries. Oregon State University

Helstad K, Nilsson AE, Fjeld DE (2001) In: Sjöström K, Rask LO (eds) Volume flexibility in wood procurement–costs and constraints for adjusting supply chain strategy. Supply Chain Management for Paper and Timber Industries. Växjö University and Timber Logistics Club, Sweden, pp 143–162

Johansson M, Erlandsson E, Kronholm T, Lindroos O (2021) Key drivers and obstacles for performance among forest harvesting service contractors–a qualitative case study from Sweden. Scand J for Res 36(7–8):598–613

Johansson M, Erlandsson E, Kronholm T, Lindroos O (2022) The need for flexibility in forest harvesting services–a case study on contractors' workflow variations. Int J for Eng 34(1):13–25

Jonsson M (2004) Wet storage of round wood. PhD thesis. Acta Universitatis Agriculturae Sueciae – Silvestria, vol. 319. Swedish University of Agricultural Sciences, Uppsala, Sweden

Jylhä P, Rikkonen P, Hamunen K (2020) Size matters–an analysis of business models and the financial performance of Finnish wood-harvesting companies. SILVA FENNICA 54(4)

Kelly MC, Germain RH (2016) Is it efficient to single-handedly run a multi-machine harvesting operation? A case study from the Northeast United States. Int J for Eng 27(3):140–150

Kogler C, Rauch P (2018) Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review. Silva Fennica, 52(4)

Kogler C, Rauch P (2023) Lead time and quality driven transport strategies for the wood supply chain. Research in Transportation Business & Management, p 100946

Kronholm T, Sosa A, Bowditch E, Pohlschneider S, Hamunen K, Rikkonen P (2019) State of the art and development needs of forestry service contractors in the Northern Periphery and Arctic region; Project report, 2019; 53

Kronholm T, Larsson I, Erlandsson E (2021) Characterization of forestry contractors' business models and profitability in Northern Sweden. Scand J for Res 36(6):491–501

Laestadius LH (1990) A comparative analysis of wood-supply systems from a cross-cultural perspective. Virginia Polytechnic Institute and State University, Diss. Blacksburg

Lindberg N (2016) Analysis of the relationship between the harvested, but not yet forwarded, volume and machine productivity in thinning and final felling operations. Report 2016:6, Dept Forest Biomaterials and Technology, Swedish University of Agricultural Sciences. [In Swedish]

Lindroos O (2012) Evaluation of technical and organizational approachesfor directly loading logs in mechanized cut-to-length harvesting. ForSci 58(4):326–341

Liski E, Jounela P, Korpunen H, Sosa A, Lindroos O, Jylhä P (2020) Modeling the productivity of mechanized CTL harvesting with statistical machine learning methods. Int J for Eng 31(3):253–262

Lundbäck M, Häggström C, Fjeld D, Lindroos O, Nordfjell T (2022) The economic potential of semi-automated tele-extraction of roundwood in Sweden. Int J for Eng 33(3):271–288

Morgan G (1998) Images of organization: the executive edition. Sage, Thousand Oaks, California

Ohno T (1988) Toyota production system: beyond large-scale production, 0th edn. Productivity

Puchkova A, Srinivasan R, McFarlane D, Thorne A (2015) Towards lean and resilient production. IFAC-PapersOnLine 48(3):2387–2392

Ringdahl O, Hellström T, Lindroos O (2012) Potentials of possible machine systems for directly loading logs in cut-to-length harvesting. Can J for Res 42(5):970–985

Skogsavtalet (2020) Kollektivavtal Skogsbruk Arbetare Mellan Gröna arbetsgivare och GS för tiden 1 November 2020–31 mars 2023. Stockholm, Sweden