



# Modelling of mechanized logging in uneven- and even-aged forest structures subject to continuous cover forestry

Teijo Palander<sup>1</sup> · Juha Lamminsalo<sup>1</sup> ·  
Kari Väätäinen<sup>2</sup> · Timo Muhonen<sup>2</sup> · Yrjö Nuutinen<sup>2</sup>

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**Abstract** The effect of forest structure affected productivity of harvester operator work in a continuous cover forest. In particular, the effects of the forests consisting of even- and uneven-age trees were compared. In addition to tree variables describing the structure of the forest, variables describing the time taken in each of the work phases were needed to accurately model the logging motions. Modelling also required single tree data from the harvester. The model precisely predicted the relationship between the variables and productivity in both the uneven-aged forest ( $R^2 = 0.96$ ) and the even-aged forest ( $R^2 = 0.92$ ). Both explanatory powers of models were statistically significant. Productivity was explained by the “volume of trunk”, the “length of the

operating part of trunk”, the “moving time of the logging device to trunk”, the “felling time of tree” and the “processing time of trunk”. In the uneven-aged forest, the effective-hour productivity was  $37.7 \text{ m}^3 \text{ E}_0\text{h}^{-1}$  and in the even-aged forest  $43.5 \text{ m}^3 \text{ E}_0\text{h}^{-1}$ . The work phases “moving the logging device to trunk” and “felling of tree” consumed more time in the uneven-aged forest. The results of the time and motion analysis justify the promotion of training both work phases to increase productivity of harvester operator work. This modelling approach can be recommended for studies on the development of selective logging method for continuous cover forestry.

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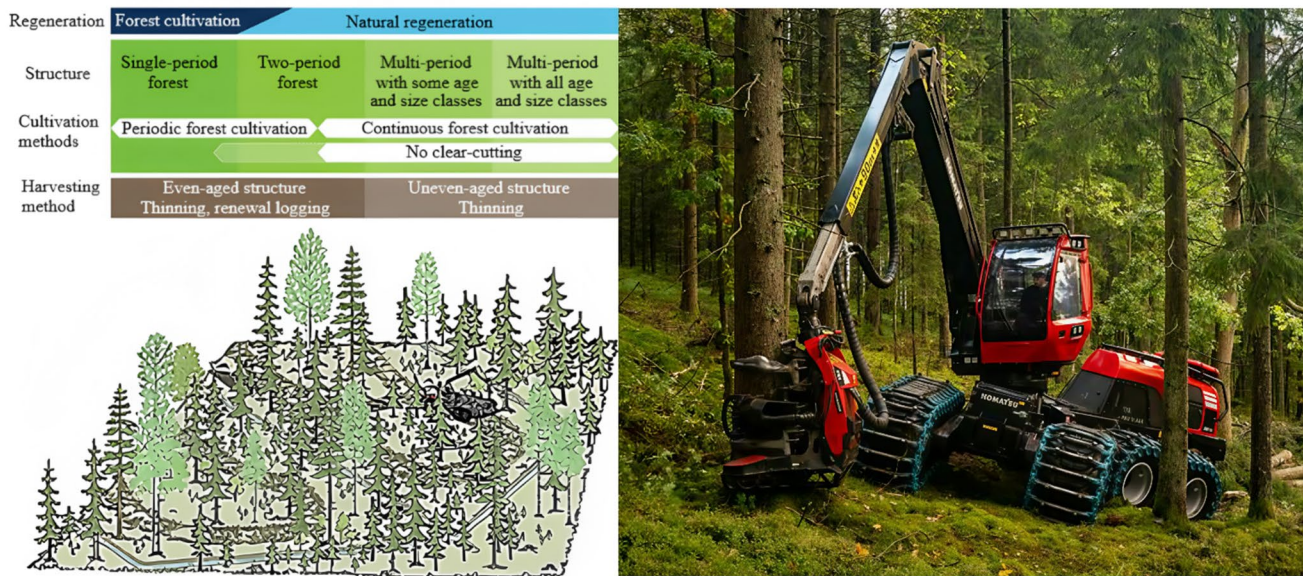
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✉ Teijo Palander  
teijo.s.palander@uef.fi

<sup>1</sup> University of Eastern Finland, P.O. Box 111, 80101 Joensuu, Finland

<sup>2</sup> Natural Resources Institute Finland, Yliopistokatu 6 B, 80100 Joensuu, Finland

## Graphical Abstract



**Keywords** Selective logging · Effective-hour productivity · Time and motion research · Work-phase analysis · Harvester operator work

## Introduction

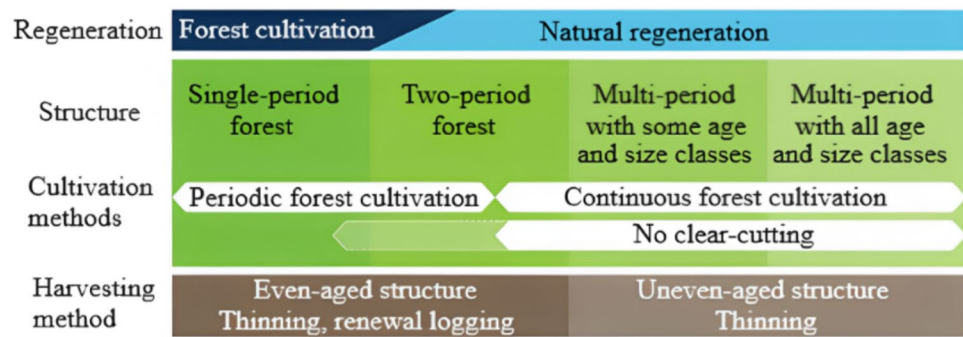
The continuous cover forestry (CCF), that is applied in the Nordic countries and Central Europe has its roots in Germany, where it was developed at the end of the nineteenth century (Gayer 1889). CCF utilizes the principle of forest management without clear cutting, where the forest is grown with a permanent tree cover. This differs from rotation forestry (RF), which always ends with clear cutting and forest regeneration, either naturally or through sowing or planting (Mason et al. 2022). Due to the milder climate and more fertile land, CCF in Central Europe has more options regarding tree species, especially due to the shade-tolerant beech. CCF has been applied there for over a hundred year (Borggreve 1891; Biolley 1901). In Finland, CCF is called selective logging (SL), and was in use until the middle of the twentieth century, when its use was completely stopped due to being harmful to the national economy (Henttonen et al. 2020). As a result, CCF was practically forbidden in Finland from the 1950s onwards. However, the demands to allow CCF to benefit nature and forest multi-use eventually grew so high that the use of CCF was permitted again from the beginning of 2014 (Rautio et al. 2025).

Following the 2014 reform, which replaced area-based taxation with taxation based on timber sales profits, several studies

have recommended selective logging (SL) as a suitable method for thinning (Lähde et al. 1999; Pukkala et al. 2014; Pukkala 2016). SL is possible to implement with different ways; however, some common principles are generally accepted. In SL, the largest trees are felled to provide growth space for the remaining trees, and the dense groups of smaller trees are thinned (Puettmann et al. 2015; Lundqvist 2017). According to the Finnish authorities, continuous cover forests usually have an uneven-aged structure in thinnings, although they can also be even-aged (Figs. 1, 2). The structure of a forest can be very even in age and uniform in size, for example, when the forest has been regenerated naturally with tree seedlings that are born under the even-aged trees.

As the climate warms, storms will increase, and so thinning methods that are less sensitive to storm damage are preferred (Blennow et al. 2010; Gregow et al. 2011; Schuck and Schelhaas 2013; Kärhä et al. 2018). On the other hand, snow may cause tree breakage, falling, growth loss and insect damage in thinned forests. Damages increase if, during thinning, too many small trees and too few large trees are left, and in too few positions (Granhus and Fjeld 2001). Therefore, in both CCF and RF, it is of the utmost importance that thinning is performed correctly, avoiding excessive removal of trees, which can cause the risk of destruction described above (Hämäläinen 2014; Sirén et al. 2015). In SL of a forest of uneven ages, proportionally more large trees are removed during thinning than in under-thinning of an even-aged forest, in which more large and stout trees that can withstand damages are left in the forest while small trees are removed.

**Fig. 1** Forestry concepts and recommendations in Finland. (Modified from Äijälä et al. 2019)



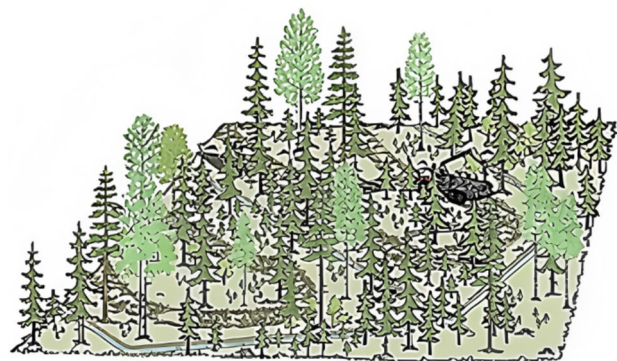
The increase in CCF was perceived positively before Finland's 2014 law reform (Kumela and Hänninen 2011), but its implementation with appropriate SL methods has not increased. This is evident from the 2020 forest use announcements, where these methods accounted for approximately three percent of all logging method options. The main challenge of CCF in the northern countries of Europe is the lack of shade-tolerant tree species. Norway spruce (*Picea abies* (L) Karst.) is the only tree species that can withstand the shading of larger trees. Another challenge is the paucity of studies and the uncertainty of their results (Valkonen and Chen 2014). In this respect, the optimization of net present values of profitability of forest management options is based on average cost data and average assumptions over a long period (Pukkala et al. 2015). Furthermore, management instructions are delivered at the stand level. For these reasons, it is difficult to compare the timber harvesting costs of CCF with RF over the entire rotation cycle of 100 years. In Sweden, in Jonsson's (2015) study, the cost of CCF harvesting during the entire rotation cycle was 28% and the fuel consumption of machinery 21% higher than costs of timber harvesting in RF. For this reason, the landowners receive less forest income from the forest they own, which usually affects decision making in a timber trade situation. There has also been considerable research on logging costs (Lindroos et al. 2024). However, this information is impossible to use in forest management at local level without updating inputs to simulation and optimization models. This study develops a model of logging productivity that can be applied to improve the accuracy of cost calculations in simulation and optimization.

Modelling and optimization of profitability of CCFs bases on old knowledge about timber harvesting and wood procurement (Rummukainen et al. 1995; Pukkala et al. 2015; Pukkala et al. 2025). Since 1995, a lot of work developing mechanised timber harvesting has been carried out in Finland. It can be stated that in this respect the cooperation with forest owners, industry and public forest organizations has been significant (Palo and Uusi-vuori 1999). An example of this is the internationally significant forest machinery production plants of Ponsse and John Deere, where logging machines are being developed for RF. Researchers of wood procurement have also understood the importance of the forest industry to the national economy. Without the forest industry, forests would be worthless. Therefore, securing the

supply of raw materials for the forest industry by using the effective logging methods of RF has been important. In practice, the intensity of thinning, tree selection and the placement of strip roads directly affect the success of the logging method (Anon. 2005). For example, an effective logging machine increases the profitability of forestry and above all influences the quality of the trees being grown (Nuutinen 2013). In addition, according to Liski et al. (2020), even 59% of variation in modelling was due to the operators. This is why the development of high-quality work also requires more information at the tree level during SL in continuous-cover forests.

In the future, the key areas of research and development will be the adaptation of SL to the work environment of CCF. Bianchi et al. (2023) have classified the structure of forests regarding the difficulty of the implementation of SL as follows: (1) "Advanced CCF" logging sites are already quite irregular in structure (i.e., height distribution) and have previously been selectively thinned in a similar manner; (2) "Medium CCF" logging sites have more irregular structure than the average RF stand in Finland but have not been selectively thinned before, and therefore need some level of transformation to be fully managed according to CCF principles; (3) "Beginning CCF" logging sites have quite a regular structure and have only been thinned using the RF underside thinning method. The first period of SL moves the forest towards an irregular structure.

In logging, e.g. the felling of trees is carried out by the operator of the logging machine. The professionalism of the harvester operator is particularly emphasized in CCF, where



**Fig. 2** A SL is targeting a forest of uneven age trees (Modified from Äijälä et al. 2019)

the perception of the working environment, work planning, competence of SL method and avoidance of damaging standing trees ultimately determines the success of the harvester operator's work. A detailed description of the logging method is the only acceptable way to clarify the work in practice (Palander et al. 2012). In this way, it is possible to verify the shortcomings and weaknesses that may occur in the method (Anon. 1992). Furthermore, based on the conclusions drawn from the results, it is possible to direct the development to the important work phases of the method. With this knowledge, the guidance, planning and implementation of logging may affect the forest growth and success of future loggings.

Time studies have been widely used as an aid to research, in which the time spent on work and its measurement is performed according to the work phase approach (Groover 2007). Today, time studies are associated with movement research, combining the time study work of Taylor and the motion study work of Gilbreth (Niebel 1988). The combination of these covers more effective practical applications. Combined time and motion research is a widely accepted research method of timber harvesting, which achieves accurate results for the development of logging methods (Palander et al. 2013).

In studies of logging, working time has traditionally been divided into work phases according to the common Nordic working time division (Anon. 1978). Later newer versions of this classification have been published, which are more suitable for studying mechanized logging work (Mäkelä 1986; Anon. 1995). Today, the automation of logging machines has made possible modern time and motion study applications at tree level that can be used to analyse logging work of a harvester operator (Ovaskainen 2009; Nuutinen 2013; Palander et al. 2013, 2025). In an automated study aimed at machine development, the effective time can be shorter, e.g., hundredths of a second (Liski et al. 2020). In this study, modern time and motion study application was applied to modelling SL work of harvester operator.

In CCF, it is important to know the effect of the structure of the forest stand on SL. We hypothesized that even- and uneven-aged forests affect the time consumption and productivity of SL. We also hypothesized that they are partly caused by the harvester operator. So far, this research problem is not modelled at tree level. In this study, SL and its productivity were modelled with the variables that described both tree and its logging work. The model is used to reveal important work phases for development of SL in CCF.

## Material and methods

### Forest structures for thinnings in CCF in RF

A case study was conducted for data collection and modelling SL method in Finland. Figure 1 shows forestry concepts and recommendations of authorities for forest management in practice, which was followed in this study. RF is on the left side of the

figure, while a successful CCF is on the right side. The renewal logging includes either clear cutting or thinning.

Forest structures of study plots were uneven-aged and -sized and even-aged and -sized before thinnings describing experimental situations in CCF and RF, respectively. Figure 2 depicts a good situation for SL in CCF.

### The forest harvester and its operator

A 6-wheeled Komatsu Forest 901 logging machine with a Komatsu C93 logging device (Fig. 3) was used for logging in the observation forest. Its theoretical maximum felling and cutting diameter is 600 mm. The boom is attached to the side of the 360-degree rotating cockpit, and its reach is 11 m. Visibility from the machine's cockpit was very good. The harvester's production data (HPR), i.e., trunk files, were collected by the information system of the machine. Files contained the identification data of the observation areas and the logging output data.

The study was carried out with one operator. He had worked as an operator for more than 10 years. He had experience in thinning, small opening and special logging sites. Here, special logging sites means electricity power lines, plots and park logging, where the variation in thickness of the trees to be felled is greater than in the usual logging of an even-aged forest. Careful directed felling of trees is also very important at these sites. He had little experience with SL for CCF.

### Logging site and observation areas

The logging site was located on a forest farm owned by the city of Joensuu, and was fertile, well-grown forest land. Most of the observation areas were Norway spruce forests. In each observation areas, SL test logging was performed on rectangular plots of 20 m × 50 m (1000 m<sup>2</sup>), except for one plot of 20 m × 40 m (800 m<sup>2</sup>). Plot number 3 was treated with small clear cutting (Fig. 4 and Table 1).

The tree-cover measurements in the observation areas were made before and after SL. After marking the observation plots, all trees with a height ≥ 1.4 m were measured for diameter at breast height (*d*<sub>1.3</sub>, mm). The distance and direction from the centre of the plot to these trees was measured. The Cartesian coordinates of trees were determined by the distance from a reference point and an angle from a reference direction (north). For every fourth tree, height (*h*, dm) was measured. A species-wise model was used to predict the unmeasured tree heights (Näslund 1936).

$$h = 1.3 \text{ m} + (d_{1.3})^2 / (a + b \times d_{1.3})^2 \quad (1)$$

where, *h* is tree height (m), *d*<sub>1.3</sub> is diameter at breast height (cm), and *a* and *b* are parameters.



**Fig. 3** Logging machine Komatsu Forest 901 equipped with Komatsu C93 logging device

Prior to and after the treatments, the number and height of undergrowth seedlings was measured (height < 1.4 m) on three rectangular sample plots of 5 m × 20 m (100 m<sup>2</sup>) systematically located on each plot. All information on the plots was recorded on a terrain data sheet. Based on the trees measured before logging, there were two main types of observation area: old growth forest with an even-aged structure and young growth forest with an uneven-aged structure.

For a more detailed comparison, the variation in the trees of observation plots 1 and 10 before and after logging is described in Tables 2 and 3. According to Bianchi et al. (2023), from the point of view of the difficulty of implementing selective logging, plot 1 is a “Medium logging site” and plot 10 a “Beginning logging site”. The structure of the

logging of these observation plots was described by diameter class distributions (Fig. 5). The trees of the growing stock in both observation plots were similar in age structure (Pukkala et al. 2016), but in observation plot 1 the proportion of small diameter trees was much higher. Therefore, it was classified as a forest of uneven-aged structure. A trunk-by-trunk examination showed that smaller trunks (< 20 cm) were also cut more there. The volume of logging (m<sup>3</sup>) was clearly weighted towards larger size classes in both observation areas.

**Time and motion study method and statistical modelling**

The time and motion study (Niebel 1988; Nuutinen 2013; Palander et al. 2012) of the harvester operator work was conducted using a video recording of the work being



**Fig. 4** Location of observation areas on the map

**Table 1** Sizes of observation areas, development class and structure of trees

Observation area	Area (m <sup>2</sup> )	Development class	Structure of trees
1	800	02	A
2	1 000	03	B
3	3 300	03	B
9	1 000	03	B
10	1 000	03	B
11	1 000	02	A
12	1 000	02	A

02, young thinning forest; 03, mature thinning forest; A, forest with uneven-aged structure; B, forest with even-aged structure

carried out in observation plots 1 and 10. One action camera was mounted inside the harvester’s cabin in the front window to film the movements of the harvester’s logging device. The study’s work phase cycle is described in Fig. 6.

A measurement priority of data was defined for each work phase. The measurement priority means that the simultaneous lower priority work phases were not used separately in the motion analysis but were included in the higher priority work phase (Nuutinen and Björheden 2016). The volume of each processed trunk was recorded through the HPR file. The operating time of the work phase motions was recorded

using the continuous timing method (Palander 2025; Palander et al. 2025). For the purposes of this research, a dedicated video analysis tool was employed to process the logging time study material.

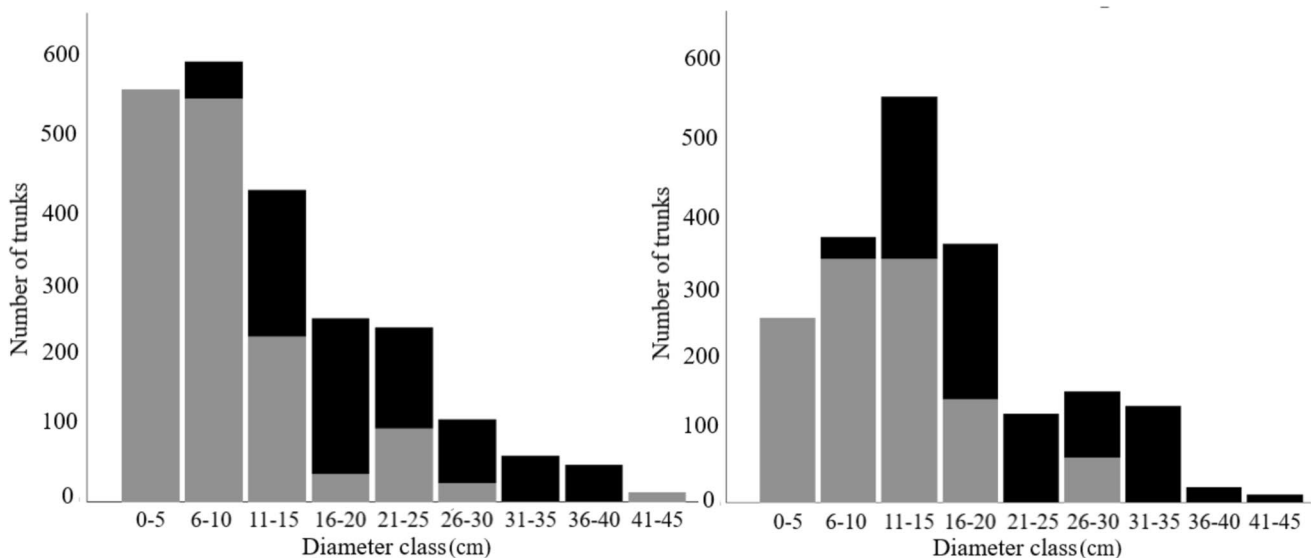
In the breakdown of work phases as motions of logging, the working time was divided into several measures, one of which was the effective work time (Fig. 7). Effective time is the time spent on actual work performance, without all interruptions. In this study’s analysis, the effective time ( $E_{\rho s}$ ,  $E_{\rho h}$ ) of the harvester operator’s work phases was calculated from working phase data collected by trunk, which is

**Table 2** Data before logging in the observation areas

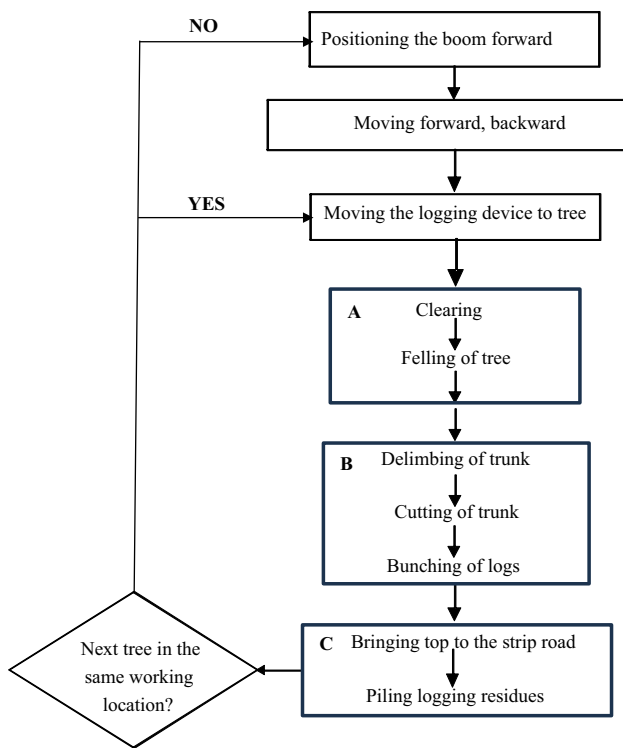
Variable	Number of trees (N ha <sup>-1</sup> )	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Volume (m <sup>3</sup> ha <sup>-1</sup> )	Mean diameter (cm)	Mean diameter weighted by basal area (cm ha <sup>-1</sup> )	Mean length of trees (m)	Mean length weighted by basal area (m ha <sup>-1</sup> )	Mean size of trees (m <sup>3</sup> )
Observation area 1	2 275	39	364.5	11.9	23.29	11.8	19.6	0.16
Observation area 10	1 750	40	368	13.3	24.51	13.3	21.13	0.169

**Table 3** Data of logging removal of trees

Variable	Number of trees (N ha <sup>-1</sup> )	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Volume (m <sup>3</sup> ha <sup>-1</sup> )	Mean diameter (cm)	Mean diameter weighted by basal area (cm ha <sup>-1</sup> )	The length of the operating part of the trunk (m)	Mean size of the trunk (m <sup>3</sup> )
Observation area 1	800	30	279	20.3	26.4	12.7	0.349
Observation area 10	830	32	316	20.8	27.7	13.7	0.381



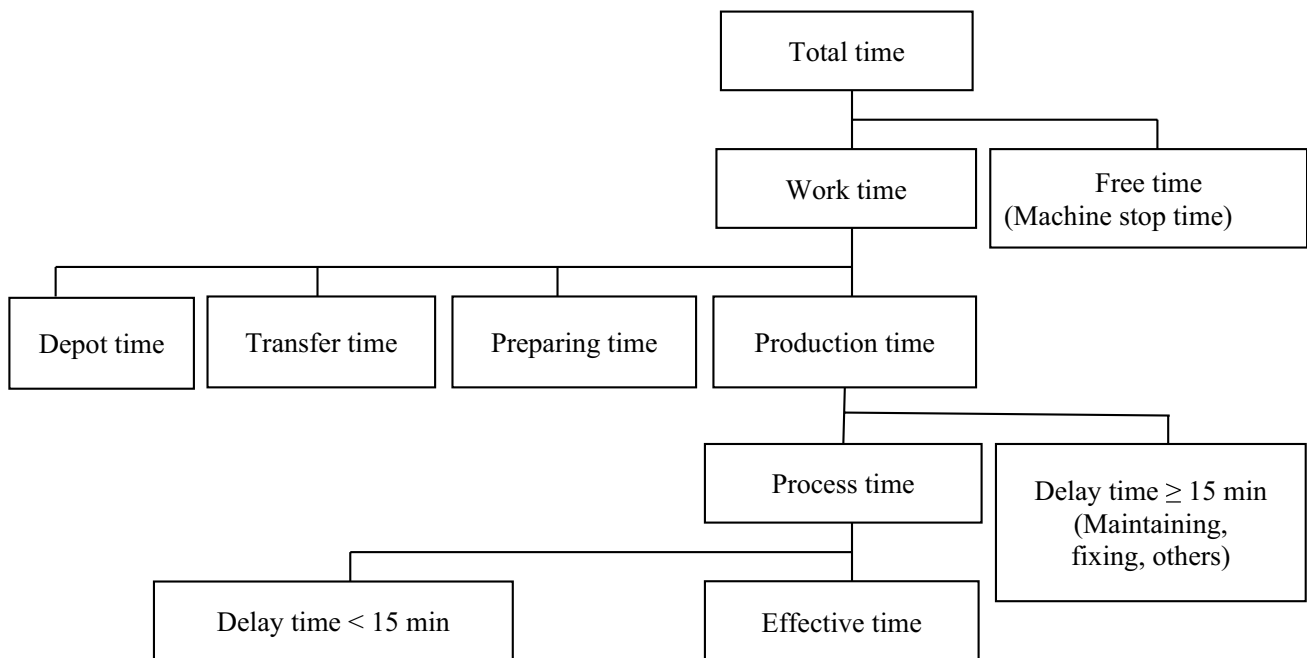
**Fig. 5** Diameter class ( $d_{l.3}$ ) distributions of trunks in observation areas 1 (left side) and 10 (right side). Black parts of bars depict distribution of removed trunks while grey bars depict distribution of trunks after logging



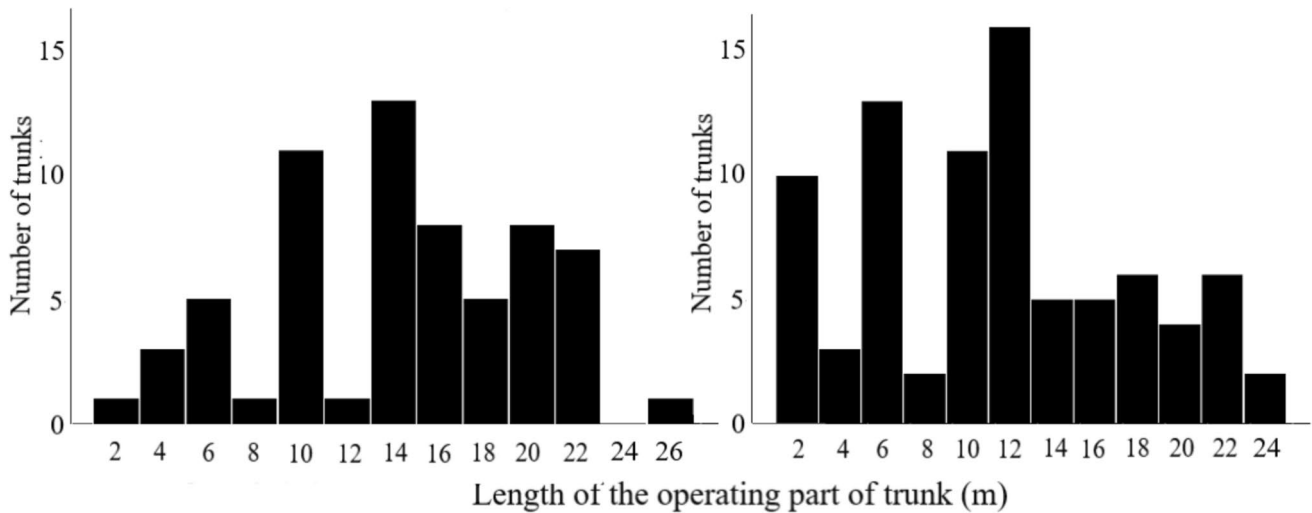
**Fig. 6** Flow chart for work phases describing the recorded work cycle of logging motion (Modified from Nuutinen 2013). Rectangles depict the higher priority work phases. A is felling of tree, B is processing of trunk, C is logging residues

accurate approach to utilize motion time recording (Palander 2025; Palander et al. 2025).

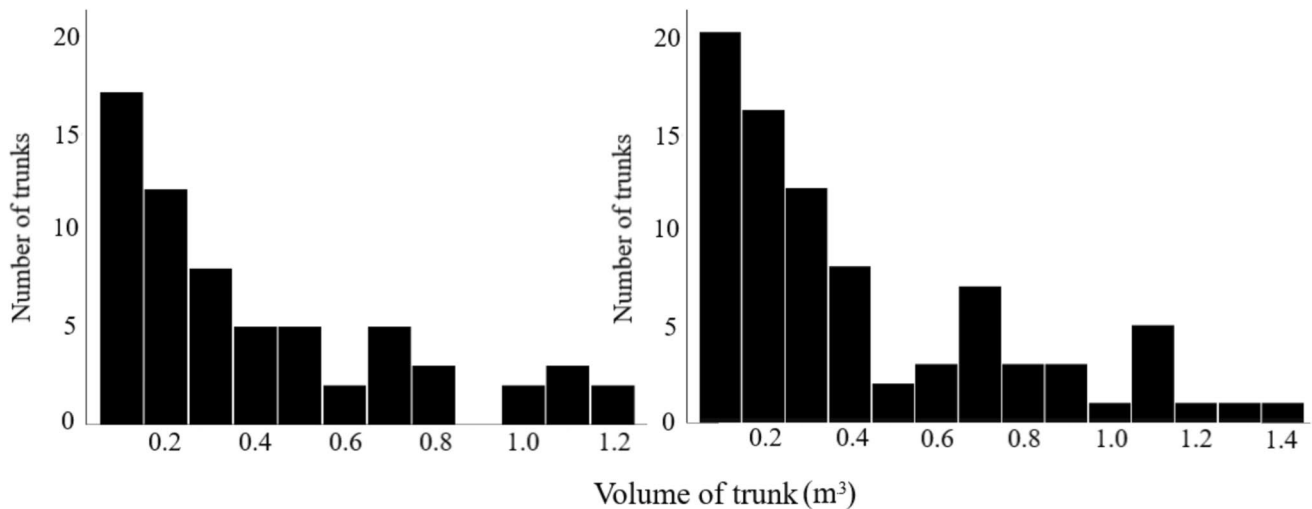
The analysis started by comparing the mean values of the data of the logging removals. After that, the distributions of potential explanatory variables of the timber logging were tested. The explanatory variables included the tree data and the time data of the work phases for logging a single trunk (Palander 2025; Palander et al. 2025). Based on the tests, there were opportunities for modelling the relationships between the variables and productivity. Statistical modelling uses mathematical models and statistical assumptions to make predictions about the real world (Henley et al. 2020). Regression analysis was performed using the SPSS-25X Statistics program (SPSS Inc. 1988). In the analysis, the explanatory variable that had the greatest effect on the model’s explanatory power ( $R^2$ ) was entered into the model first. The modelling process was continued if the new variables increased the degree of explanation ( $R^2$ ) or were relevant from the point of view of the whole. The variable was considered statistically significant if the p-value was lower than 0.05. To achieve the aim of the study, several models were tried. The results are presented for the best models for observation areas 1 and 10.



**Fig. 7** Division of working time in logging (Modified from Mäkelä 1986)



**Fig. 8** Length distribution of the operating part of trunk (m) from observation area 1 (left side,  $n=64$ , mean=12.71 m, standard deviation=4.69 m) and from observation area 10 (right side,  $n=83$ , average=13.69 m, standard deviation=5.21 m)



**Fig. 9** Volume distribution of removed trunks ( $m^3$ ) from observation area 1 (left side,  $n=64$ , Mean value=0.349  $m^3$ , Standard deviation=0.317  $m^3$ ) and from observation area 10 (right side,  $n=83$ , Mean=0.381  $m^3$ , Standard deviation=0.344  $m^3$ )

## Results

### Significant tree variables

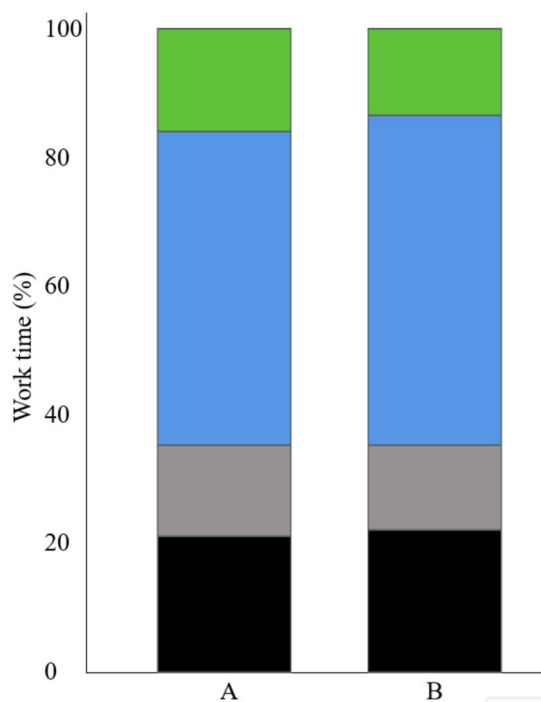
The length of the operating part of the trunk and the volume of the removed trunk were statistically different in observation areas 1 and 10, whose distributions were illustrated with histograms (Figs. 8, 9).

### Work phases of logging

In both observation areas 1 and 10, the “processing of trunk” (delimiting and cutting of trunk) were proportionally (about

50%) the most time-consuming work phase (Fig. 10). The “moving the logging device to trunk” took about 21.5% of the logging time, “felling of tree” 13.5% and “auxiliary time” 14.5%. All other work phases were combined with the auxiliary time because their importance to work productivity was minor.

Distribution of the effective working time of the trunk ( $E_{\rho s}$  per trunk) was also described by the histogram per number of trunks (Fig. 11). In an even-aged forest, the time spent on logging the trunk was more evenly distributed. In the distribution, logging times that were more frequent than others were also clearly visible (15–20  $E_{\rho s}$  per trunk).



**Fig. 10** Average proportion of work phases (%) of total work time ( $E_0s$ ) in observation area 1 and 10, A and B respectively. Black depicts “moving of the logging device to trunk”, grey depicts “felling of tree”, blue depicts “processing of trunk”, green depicts “auxiliary time”

**Modelling motion times of the harvester operator work**

Based on the tests, the “moving time of the logging device to trunk”, “felling time of tree”, “processing time of trunk”, the “length of the operating part of trunk” and the “volume of trunk” were selected as potential explanatory variables to total logging time. The “processing time of trunk” included the time spent on “delimiting and cutting the trunk”. The analysis showed that the “volume of trunk” and the “length of the operating part of trunk” were not statistically significant explanatory variables for logging motions. Therefore, the total time consumed on logging was only modelled with work phase variables, the relationship of which is described by model 2. Tables 4 and 5 show the results of the application of the model in observation areas 1 and 10.

$$F_i = \beta_0 + \beta_1 \cdot T_i + \beta_2 \cdot K_i + \beta_3 \cdot P_i + \epsilon_i \tag{2}$$

where,

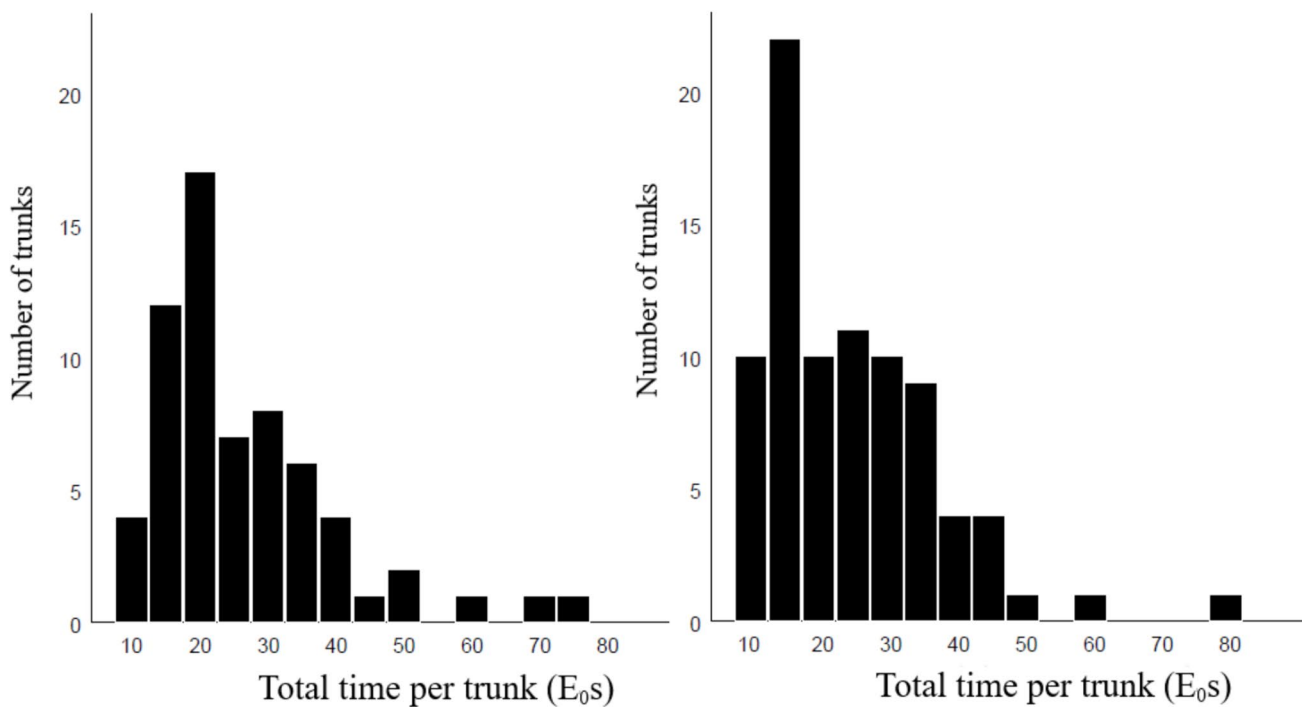
$F_i$  is the total time ( $E_0s$ ) consumed for logging tree trunk  $i$ ;

$T_i$  is the time ( $s$ ) consumed for the moving of the logging device to tree trunk  $i$ ;

$K_i$  is the time ( $s$ ) consumed for felling of tree trunk  $i$ ;

$P_i$  is the time ( $s$ ) consumed for processing tree trunk  $i$  (delimiting and cutting);

$\beta_0$  is the value of the constant term;



**Fig. 11** Distributions of logging time ( $E_0s$  per trunk) in observation areas 1 (left side) and 10 (right side)

$\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are regression parameters for explanatory variables  $T_i$ ,  $K_i$ , and  $P_i$ ;

$\varepsilon_i$  is the residual value of unexplained variation.

### Modelling productivity of the harvester operator work

In the uneven-aged forest, the effective-hour productivity was  $37.7 \text{ m}^3 E_0h^{-1}$  and in the even-aged forest  $43.5 \text{ m}^3 E_0h^{-1}$ . Productivity was first modelled only with work phase variables. In the even-aged forest (observation area 10), the linear regression model explained a larger proportion ( $R^2=0.40$ ) of the productivity than in the uneven-aged forest of observation area 1 ( $R^2=0.27$ ). The “processing time of trunk” was statistically significant ( $p < 0.01$ ) in both observation areas. Among the explanatory variables, the “felling time of tree” was better suited to the model of the observation area with the even-aged structure, because it became a statistically significant variable ( $p=0.001$ ) unlike in the forest of uneven-aged structure ( $p=0.129$ ). It is also worth mentioning that the “moving time of the logging device to tree” was an almost statistically significant ( $p=0.051$ ) variable when explaining productivity in a forest of uneven-aged structure, in contrast to a forest of the even-age structure ( $p=0.747$ ).

Productivity was also modelled by adding the “volume of trunk” ( $\text{m}^3$  per trunk) and the “length of the operating part of trunk” (m) to the group of explanatory variables. Model 3 describes this situation. The corrected explanatory power considers the addition of the variables and the number of explanatory variables included in the model. Tables 6 and 7 show the results of the application of model 3 in observation areas 1 and 10. In a forest with an uneven-aged structure (observation area 1), the linear regression model explained a larger proportion ( $R^2=0.96$ ) of productivity than in the even-aged forest of observation area 10 ( $R^2=0.92$ ). In both forests, all other variables explaining productivity were statistically highly significant except for the “moving time of the logging device to tree” and “felling time of tree”. In model 3, the “felling time of tree” was better suited to the model of the observation area with the even-aged structure, because it was a statistically significant variable ( $p=0.003$ ) unlike in the forest of uneven-aged structure ( $p=0.076$ ). The “moving time of the logging device to tree” was a statistically significant ( $p=0.039$ ) variable explaining productivity in a forest with an uneven-aged structure, in contrast to the even-aged forest ( $p=0.098$ ). However, it is worth mentioning that in both forests the ability of these variables to explain productivity was more significant when the extended model 3 was used.

$$F_i = \beta_0 + \beta_1 \cdot V_i + \beta_2 \cdot L_i + \beta_3 \cdot T_i + \beta_4 \cdot K_i + \beta_5 \cdot P_i + \varepsilon_i \quad (3)$$

where,

$F_i$  is the logging productivity of tree trunk  $i$  ( $\text{m}^3/E_0h$ );

$V_i$  is the volume of trunk  $i$  ( $\text{m}^3$ );

$L_i$  is the length (m) of the operating part of the trunk  $i$ ;

$T_i$  is the time (s) consumed for the move of the logging device to trunk  $i$ ;

$K_i$  is the time (s) consumed for felling of tree trunk  $i$ ;

$P_i$  is the time (s) consumed for processing tree trunk  $i$  (delimiting and cutting);

$\beta_0$  is the value of the constant term;

$\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\beta_4$ , and  $\beta_5$  are regression parameters for explanatory variables  $V_i$ ,  $L_i$ ,  $T_i$ ,  $K_i$ , and  $P_i$ ;

$\varepsilon_i$  is the residual value of unexplained variation.

## Discussion

### The work phases that affect time consumption in SL

A video was filmed for every tree in both the uneven-aged and even-aged forests, from which the effective time consumptions ( $E_0s$ ) of the work phases of the harvester operator were recorded. According to the classification by Bianchi et al. (2023), even-aged forests can be assigned to class (iii), whereas uneven-aged forests correspond to class (ii). Both logging experiments (SLs) aimed at CCF for future management. The motion times of the work phases could be clearly determined, from which their time proportions could be calculated (Fig. 10). With the tree level analysis carried out by trunk, it became clear (model 2) that the “moving the logging device to the trunk” and “felling of tree” were important work phases from the point of view of the development of SL in CCF. This novel information becomes available only through tree-level analysis. Their average shares of the total time used ( $E_0s$  per trunk) were respectively 21.5% and 13.5%, i.e., a total of 35%. This relative share of the total time consumption is important in practical work, so training could be targeted at both work phases to increase the speed of SL of CCF.

Model 2 revealed that both work phases the “moving the logging device to the trunk” and “felling of tree” affected the total time consumption of SL differently between the forest with the uneven-aged structure and the forest with the even-aged structure (Tables 4 and 5). At the same model, the effect of the “processing of trunk” was the same in both work environments. It is also noticeable that the effect of the constant term was greater in the uneven-aged observation area. The relationships described by model 2 allow us to conclude that SL in forests of uneven-aged structures consume more time during the work phases that precede the “processing of trunk”. More time was also spent before moving the logging device to the trunk, because the effect of the constant term on the total effective time consumption of logging of the trunk was greater. These analyses of the

time consumption of separate work phases support general suggestions about the need for education about SL and CCF.

**Factors affecting productivity of SL in CCF**

The productivity ( $m^3/E_0h$ ) is the most important output variable that directly affects cost effectiveness, timber price and profitability of operations (Lindroos et al. 2024). The productivity of SL was modelled first only with work phase variables ( $E_0s$ ) and secondly by adding tree variables the “length of the operating part of the trunk” (m) and the “trunk volume” ( $m^3$  per trunk) to the set of explanatory variables (Figs. 8 and 9). As expected, the degree of explanation increased in the latter model (model 3). Several studies have used trees’ volume as a variable of productivity models and justified that tree trunk shape affects productivity (Labelle et al. 2016; Liski et al. 2020). If only work phase variables were used in the modelling, it explained a larger proportion ( $R^2=0.40$ ) of the productivity in the even-aged forest than in the uneven-aged forest ( $R^2=0.27$ ). When the “trunk volume” ( $m^3$ ) and the “length of the operating part of the trunk” (m) were added to the modelling, the roles changed (model 3). Tables 6 and 7 show that in the even-aged forest, model 3 explained a smaller proportion ( $R^2=0.92$ ) of the productivity than in the uneven-aged forest ( $R^2=0.96$ ). In the latter applications of the model, however, the difference in the explanatory power was smaller. The results reveal that productivity modelling is less accurate with work phase variables, even if the data is collected by trunk. Therefore, the precision modelling of productivity can be achieved using the following explanatory variables: “moving time of the logging device to the trunk”, “felling time of trunk”, “processing time of trunk”, “length of the operating part of the trunk” and “trunk volume”. A similar model structure ( $R^2=0.95$ ) has previously been used at local level to develop logging methods in plantation forests (Palander et al. 2025). When Liski et al. (2020) used large scale data for prediction of productivity, their application reached  $R^2$ -value of 0.89.

Model 3 reveals critical work phases for increasing productivity of SL, which is possible both with new machinery

**Table 4** Parameter values of the model 2 for the total time consumption of logging motions of trunk for harvester operator work in observation area 1.  $\beta_0$ =constant,  $\beta_1$ =moving time of the logging device to trunk  $i$ ,  $\beta_2$ =felling time of tree  $i$ ,  $\beta_3$ =processing time of trunk  $i$  (delimiting and cutting)

Number of trunks	Parameter	Coefficient	$t$ -value	$p$ -value	$R^2$
64	$\beta_0$	4.656	13.476	<0.001**	0.997**
	$\beta_1$	0.973	20.861	<0.001**	
	$\beta_2$	0.894	12.561	<0.001**	
	$\beta_3$	1.057	88.277	<0.001**	

\*, \*\*Statistical significance is <0.05 or <0.001, respectively

**Table 5** Parameter values of the model 2 for the total time consumption of logging motions of trunk for harvester operator work in observation area 10.  $\beta_0$ =constant,  $\beta_1$ =moving time of the logging device to trunk  $i$ ,  $\beta_2$ =felling time of tree  $i$ ,  $\beta_3$ =processing time of trunk  $i$  (delimiting and cutting)

Number of trunks	Parameter	Coefficient	$t$ -value	$p$ -value	$R^2$
83	$\beta_0$	2.605	2.861	0.005*	0.945**
	$\beta_1$	0.789	6.447	<0.001**	
	$\beta_2$	1.568	7.730	<0.001**	
	$\beta_3$	1.051	23.536	<0.001**	

\*, \*\*Statistical significance is <0.05 or <0.001, respectively

and by training the operator. In general, productivity increases if work techniques are learned well by the operator (Ovaskainen 2009). Therefore, the work phases “moving the logging device to the trunk” and “felling of tree” were considered carefully in both applications of model 3 (Tables 6 and 7). According to model 2, they were important work phases in SL and could be included in education on work techniques (Tables 4 and 5). Because their variation for single trees was larger in model 3, the results justify training

**Table 6** Parameter values of the linear regression model for logging productivity of trunk in observation area 1.  $\beta_0$ =constant,  $\beta_1$ =volume of trunk  $i$ ,  $\beta_2$ =length of operating part of trunk  $i$ ,  $\beta_3$ =moving time of the logging device to trunk  $i$ ,  $\beta_4$ =felling time of tree  $i$ ,  $\beta_5$ =processing time of trunk  $i$

Number of trunks	Parameter	Coefficient	$t$ -value	$p$ -value	$R^2$
64	$\beta_0$	4.893	1.498	0.139	0.956**
	$\beta_1$	76.575	15.020	<0.001**	
	$\beta_2$	0.023	7.778	<0.001**	
	$\beta_3$	-0.708	-2.108	0.039*	
	$\beta_4$	-0.934	-1.807	0.076	
	$\beta_5$	-1.067	-9.463	<0.001**	

**Table 7** Parameter values of the linear regression model for logging productivity of trunk in observation area 10.  $\beta_0$ =constant,  $\beta_1$ =volume of trunk  $i$ ,  $\beta_2$ =length of operating part of trunk  $i$ ,  $\beta_3$ =moving time of the logging device to trunk  $i$ ,  $\beta_4$ =felling time of tree  $i$ ,  $\beta_5$ =processing time of trunk  $i$

Number of trunks	Parameter	Coefficient	$t$ -value	$p$ -value	$R^2$
83	$\beta_0$	15.154	3.924	<0.001**	0.920**
	$\beta_1$	84.629	12.998	<0.001**	
	$\beta_2$	0.017	5.187	<0.001**	
	$\beta_3$	-0.565	-1.674	0.098	
	$\beta_4$	-1.973	-3.021	0.003*	
	$\beta_5$	-1.228	-7.263	<0.001**	

\*, \*\*Statistical significance is <0.05 or <0.001, respectively

needs of them. Training could decrease variation between single trees. In addition to developing SL method, the same model structure could also be used to manage or even reduce fuel consumption and emissions (Palander 2025). Based on increased total time consumption and smaller productivity, it can be assumed that in the uneven-aged continuous cover forests, the fuel consumption in thinning operations is higher than in the same operations in the conventionally managed rotation forests.

### Justification of modelling

Forests of uneven-aged structures are necessary for the success of CCF but creating them is challenging. Current Finnish forests are the result of the decades of implementation of RF with management guidelines on sustainability (Anonymous 2025). The observation areas 1 and 10 of this study had also previously been managed with this principle. In this study, an aim was to use SL so that young trees or those smaller than the dominant trees would remain in the forest, which would enable an uneven-aged structure needed for CCF (Äijälä et al. 2019). In Nordic countries, the most important trees for near-term timber production are those 5–15 m high. According to numerous studies, 10–20% of them are damaged in the first SL (Hämäläinen 2014; Sirén et al. 2015). This damage was not measured, but SL of observation area 1 was slightly too focused on dominant trees (Fig. 6). As Bianchi et al. (2023) have suggested, the complexity of mechanical logging of CCF varied a lot depending on the stand structure. In the transition from the even-aged structure of forest to the uneven-aged structure of CCF, large and small trees should have been more evenly targeted for removal. Furthermore, birch and pine should have been preferentially left behind. It would perhaps be possible to obtain more useful results from modelling if in the future we could find more forests adjusted to the uneven-aged structures. This will take at least a generation, if the current observation forests are spared from the destruction that threatens them. Hopefully, the shade-tolerant beech will provide more options for CCF in Nordic countries, as in Central Europe.

There has been very little research on the development of SL methods for CCF in Finland. In this study, the operator was instructed to raise the trunk 45 degrees so that the logging residues would fall onto the strip road, which was successful. Otherwise, the work techniques used in SL differed only slightly from the usual under-thinning of RF (Ovaskainen 2009), and due to the age and size structure of the observation areas, SL involved a combination of methods previously learned by the operator. In the future, the key research and development areas will be the adaptation of SL to the changing work environment. The findings of this study highlight the significance of tree shape and volume

for logging productivity (Labelle et al. 2016). Tree shape influenced the effective “length of the operating part of the trunk”. In the future, tree selection may increasingly occur at the operational point level, facilitated by the automation of harvesters, which could enable more efficient SL methods in terms of time consumption, productivity, and stem quality.

After 2014 forest owners have been subject to capital gains taxation, which means that tax is only paid on the income from the forest after the sale of the timber (Henttonen et al. 2020). Forest owners are also free to use CCF and SL (Lähde et al. 1999; Pukkala et al. 2014; Rautio et al. 2025). Before 2014, forest owners paid taxes to society annually based on the wood yield per hectare of the forest they owned. It was a calculated income based on the determined growth of the trees. If the forest grew well, producing the maximum volume of wood every year, the income of the forest owner calculated in money was also maximized. In this respect, research based on reality is still lacking, which would reveal to forest owners the loss of profits and income caused by the loss of tree growth related to CCF. The losses in wood sales income are partly caused by SL because logging is more expensive in CCF than in RF (Jonsson 2015). This study confirmed this result, because productivity decreased in uneven-aged structure. Decreasing productivity increases cost of logging as studies have reported (Lindroos et al. 2024). Therefore, it also decreases the unit price paid by the forest industry to the forest owner per cubic meter of wood (EUR m<sup>-3</sup>). Forest management recommendations have traditionally relied on stand-level data analysed through simulation and optimization models (Pukkala 2016, 2022; Pukkala et al. 2015). More recently, a tree-level approach has been introduced (Pukkala et al. 2025). However, this application still relies on outdated logging data (Rummukainen et al. 1995) and could be further refined by incorporating the tree-level results of the present study.

### Conclusions

The effect of even-aged and uneven-aged forest structures on harvester operator work in SL of CCF was investigated. Forest structure had a pronounced effect on the productivity of selective logging, whereas the influence of the harvester operator was comparatively minor. The developed model precisely predicted productivity in a forest with uneven-aged structure ( $R^2=0.96$ ) and a forest with even-aged structure ( $R^2=0.92$ ). Productivity was accurately explained by the “volume of trunk”, “length of the operating part of trunk”, “moving time of the logging device to trunk”, “felling time of tree” and “processing time of trunk”. Usually, these variables have been based too much on average values

for the modelling to be accurate enough to draw plausible conclusions. This study showed that precision modelling requires separate tree data and trunk data of trees. Therefore, the time and motion study could clearly reveal potential work phases of logging for improvement of SL for CCF. The work phase variables of “moving the logging device to trunk” and “felling of tree” consumed more time in the uneven-aged structure. In fact, the practice of these work phases should be promoted thorough training to increase work quality and productivity. The research aims were achieved, and the models can be used to analyse the performance of the harvester operator work and SL. Therefore, this modelling structure can also be recommended for management studies on the sustainable CCF.

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**Data availability** The sample plot data is available upon reasonable request from YN.

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