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PERFORMANCE OF A LIEBHERR 451-13 HANDLER IN LOG MOVING AND PILING OPERATIONS

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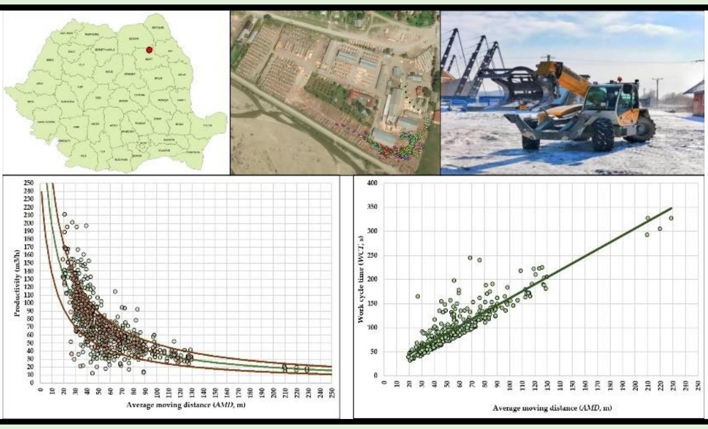
HIGHLIGHTS

- Cycle time, fuel consumption and productivity depend on movement distance in log handling operations.
- Time and fuel consumption models are linear in relation to average movement distance.
- Productivity decreases sharply in the models as a function of average movement distance.

GRAPHICAL ABSTRACT



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ABSTRACT

Performance assessment studies are essential in forest operations for optimizing larger systems, setting working rates, evaluating environmental performance and cost control. Studies on log handling operations are rare in the existing literature. This study evaluates the operational performance in terms of time, fuel consumption and productivity for a Liebherr 451-13 log handler in a wood storage facility. For coniferous logs of 4 m in length, a movement distance ranging from 30 to 500 m, a mean payload of 2.28 logs per turn averaging 1.68 m^3, net efficiency and productivity were estimated at 0.016 h/m^3 and 61.66 m^3/h, respectively. Systematically sampled GPS (Global Positioning System) speed was used to estimate the movement speed and distance which were then used to model time, fuel consumption and productivity as functions of the average movement distance. The developed models characterize the productivity functions of the observed operations and provide hints on potential improvements. Planning carefully the operations in terms of machine's operational coverage has the potential of improving the productivity and unit fuel consumption.

Keywords:
Updated equipment
Log moving and piling
Time consumption
Fuel consumption
Productivity

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1. INTRODUCTION

Evaluation of time and fuel consumption as well as of productivity is an essential component of forest operations research because it provides informed grounds and the data needed for optimization, work rate setting, cost control and environmental accounting; typically, it is implemented in the form of time and motion studies which account for production outputs and fuel use in operations [1]. Since the use of updated technology is a driver of sustainability in operations [2], an important application of time and motion studies is that of evaluating the performance of newly introduced or significantly changed equipment, technologies or methods of work, with the aim of characterizing their behavior in known or new operational environments. On the other hand, keeping records on the performance of operations in various setups is important for both practical and scientific applications.

The scientific literature is abundant in studies reporting on the performance of operations developed in the forests. As examples, review studies have collected a significant body of knowledge on the operational performance of motor-manual felling [3], skidding [4,5] and cable yarding [6], as well as on the share of partly and fully mechanized working methods in forest operations [7]. On the other hand, availability of data on the performance of log handling operations implemented in wood storage facilities is scarce, particularly for new generation equipment.

In Romania, for instance, there are work rates developed in the past for the Romanian-made front loaders (IFRON), which set the productivity and time consumption rates in wood sorting and grading facilities by considering factors such as the condition of the ground (paved/unpaved), species (broadleaved/coniferous), thickness of the logs (less or more than 16 cm) and the movement distance as categories [8]. Similar factors are considered to set the fuel consumption rates for operations implemented in wood storage facilities by Romanian-made front loaders [9], and both, or similar rate setting standards are currently used by the National Forest Administration – RNP Romsilva to set work rates, fuel consumption and to make payments.

However, the machine fleet has been continuously upgraded in all the working places by purchasing significantly changed technology, while the working methods have changed to reflect the new configuration of the supply chain, in which the transportation of wood from the forest to the mills or to the storage facilities is dominantly done as wood assortments, particularly when dealing with coniferous wood. As such, the existing rate setting standards reflect only to a limited extent the way in which the log handling operations are currently implemented in wood storage facilities.

The goal of this study was to evaluate the operational performance of a new-generation log handler in moving, sorting and grading operations implemented for coniferous wood assortments in a wood storage facility. The first objective of the study was to characterize the structure of operational time consumption and to model the work cycle time as a function of log movement distance. The second objective of the study was to evaluate and model the fuel consumption as a function of operating distance. The third objective of the study was to evaluate and model efficiency and productivity of log handling operations by considering the information collected in the field as well as the data yielded by the models developed to characterize the time consumption.

2. MATERIALS AND METHODS

2.1. Study location

This study is based on data collected between 23 and 26 of November 2021 in a wood storage facility located in Neamţ County of Romania (**Figure 1a**). The wood storage facility is managed by Târgu Neamţ Forest District of the Neamţ Forest Directorate, which is one of the county-level forest directorates of the National Forest Administration (RNP Romsilva), being located near the Târgu Neamţ City. It is composed of several wood storage and processing facilities, the main of which is the wood sawmilling facility which is designed to saw logs with diameters in range of 20 and 80 cm and lengths of 3 to 6 meters. Typically, the logs are supplied to the storage facility from the surrounding forests; the processing operations are dominated in the facility by coniferous logs (99% spruce and fir), while broadleaved logs such as beech represent less than 1% of the inputs.

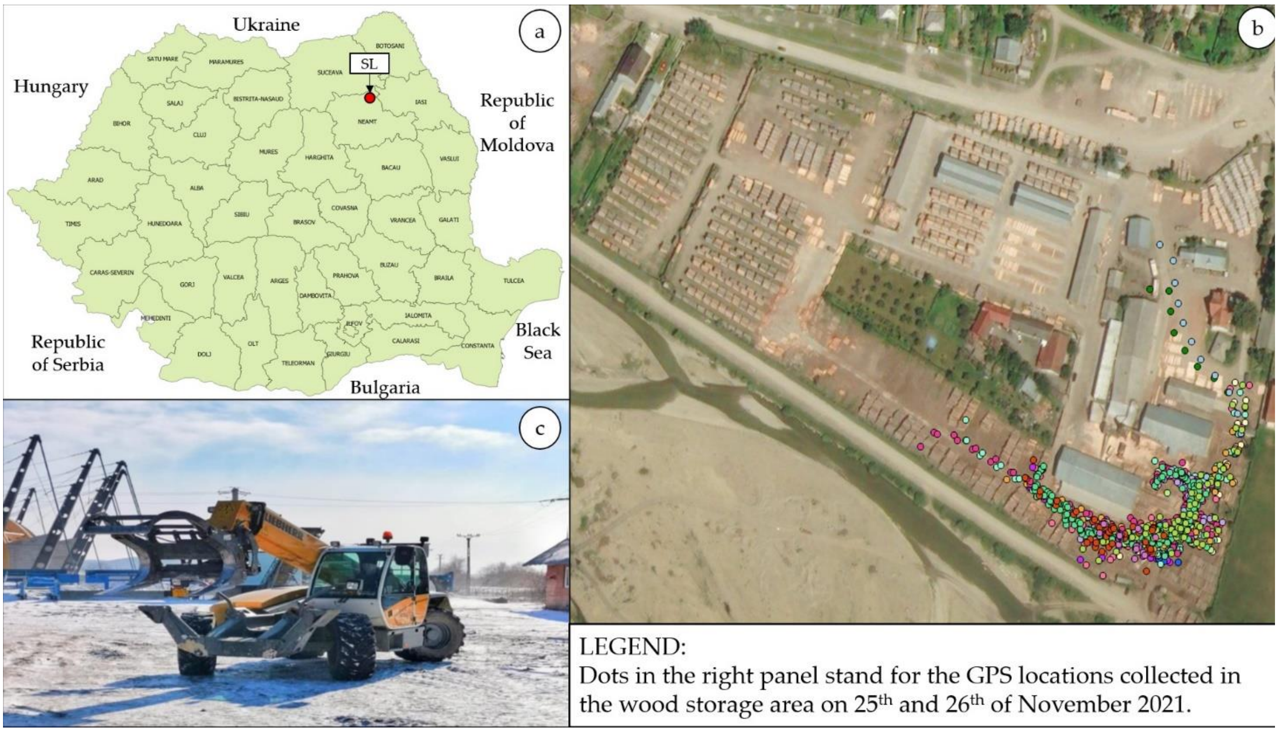


Figure 1. Study location and machine description: a – study location at the national level, b – wood storage facility, c – machine taken into study. Source: maps are designed in QGis based on freely available thematic layers and Bing ® aerial imagery.

As a general work organization, the logs are unloaded and piled by taking into consideration their diameter and length category (typically between 24 and 80 cm in diameter and 3 and 4 m in length). In this study, the length of the logs varied between 3 and 8 m, with the latter accounting for few logs which were crosscut to obtain logs of 4 m, which was the dominant length of the logs as observed in the field. Also, the internal log transportation distances varied between ca. 30 and 500 m, depending on the pile used to move them to the sawmill or to other locations within the storage facility. During the data collection activities, the air temperature was relatively low, varying between 5 and 7 °C and the condition of the ground was good.

2.2. Machine description

The machine taken into study was a Liebherr 451-13 telescopic handler (**Figure 1c**) equipped with a 74 kW John Deere, four-cylinder water-cooled diesel engine having a displacement of 4.5 l. The maximum moving speed is of 25 km/h and the machine was equipped with a four-wheel drive. Lifting capacity depends on the distance and height at which the payload is lifted from the ground, varying between 1 and 5 tons. The machine was equipped with a specialized grapple (**Figure 1c**) for log handling and transportation and it was operated by an experienced worker who was assisted in operations by the manager of the wood storage facility.

2.3. Work organization

The observed work tasks consisted of moving the logs from the piles in which they were stored to new piles either to feed the sawmill or to prepare the wood for further transportation. In both cases, the wood was sorted and graded, which included measurements. The time consumption and work elements considered in this study are described in **Table 1**.

Table 1. Description of time and work elements

Time & work element	Abbreviation	Description
Total time	*TT*	Total time observed during the field study, including delays caused by various reasons
Productive time	*PT*	Time in which productive tasks were observed. It excluded the delays caused by study and technical reasons, as well as meal time
Delay time	*DT*	Time spent to setup and take down the measurement devices as well as to make measurements, to have meals, and to solve technical problems
Delays caused by study	*SDT*	Time spent to setup and take down the measurement devices, as well as to make fuel and production measurements during which the work was interrupted
Meal time	*MT*	Time spent to have meals
Delays caused by technical reasons	*TDT*	Time spent to solve technical problems
Empty turn movement time	*ETMT*	Time spent during empty turn
Empty turn rear movement time	*ETRMT*	Time spent during empty turn by rear movement
Empty turn forward movement time	*ETFMT*	Time spent during empty turn by forward movement
Loading time	*LOADT*	Time spent to grab/take the logs from a pile
Loaded turn movement time	*LTMT*	Time spent during loaded turn
Loaded turn rear movement time	*LTRMT*	Time spent during loaded turn by rear movement
Loaded turn forward movement time	*LTFMT*	Time spent during loaded turn by forward movement
Unloading time	*UNLOADT*	Time spent to place the logs into a pile
Workplace cleaning time	*CLEANT*	Time spent to move small log ends

The organization of work was relatively simple, and it consisted from grabbing the logs from piles and delivering them to new, log-graded piles, which supposed empty turn on the machine, log loading, loaded turn and log unloading. In several cases, small ends of logs were moved to designated places to clear the workplace. Empty and loaded turns were made by moving the machine in both directions (forward and backward), therefore the study accounted for such movements. Breaking points of the work elements were based on accounting for that moments in which a specific event started to occur. As an example, loading was considered to start when the first maneuvers of the telehandler occurred, although the machine was still slowly moving towards a pile; each time, this occurred close to the piles from which the wood was taken. To forward and rear movements were given the starting and ending points at those moments in which one of the two ended.

2.4. Data collection

Data collection aimed at accounting for the time and fuel consumption, and for production measurement. Since measuring the distance was difficult by regular means, for each work cycle it was estimated based on the speed extracted from systematically collected GPS (Global Positioning System) locations by the means of a smartphone-based application. To do so, a smartphone was placed in the machine and measurements were taken in the last two days of observation by using the Geo Tracker app (version 5.1.5.2972), which is able to export .gpx files for use in external mapping software. To collect data on time consumption, a GoPro Hero 10 video camera was placed on the machine with the field of view oriented towards the front part so as to properly cover the operations done by the machine. The camera was powered by an external energy source (24000 mAh) and set to continuously collect video files at high resolution. Fuel consumption was measured by the refilling to full method [1,10,11] following the completion of a number of work cycles which varied between 7 and 13. It consisted of using hard polymer graded cylinders to determine the quantity of fuel consumed during the completion of the work cycles as mentioned above and the quantities determined by differences were noted in a field book along with the corresponding work cycles. The measurements were taken to the nearest 100 centiliters. Production was estimated at a work cycle resolution by noting the species and the number of logs transported between piles and by measuring the length and end diameters of each log. Diameter measurements were taken to the nearest centimeter while the log length measurements were taken to the nearest meter. The measurements on log biometrics were taken at the piles in which the logs were placed by the machine. At the office, Huber’s formula was used to estimate the volume of each log, which was the used to account for the volume of each load and for the volume of production. Data describing the biometrics of each log and load, as well as the data on fuel consumption were noted in the field book. Video files were downloaded into a personal computer at the end of each observation day and the data collected by smartphone app was exported and stored as .gpx files. Data was collected from the field based on informed consent of the observed workers who agreed to participate in the study and who were instructed to work as usual.

2.5. Data processing and statistical analysis

2.5.1. Time consumption

Video files were analyzed in detail by running them in the free VLC Media Player software (Video LAN Organization, www.videolan.org). Time consumption for each work cycle was determined by observing the events and noting the starting and ending time of each work element as described in **Table 1**. Then, the duration of each time element was computed as the difference between the ending and starting time. The work of [1,12] was used as a guideline for the time consumption analysis. **Equations 1-3** describe the time elements included in a typical work cycle.

$$WCT \text{ [s]} = ETMT \text{ [s]} + LOADT \text{ [s]} + LTMT \text{ [s]} + UNLOADT \text{ [s]} \quad (1)$$

Where:

WCT - time spent to complete a work cycle, excluding delays; *ETMT* - time spent during empty turn in a work cycle, *LOADT* - time spent to grab the logs in a work cycle, *LTMT* - time spent during loaded turn to move the logs in a work cycle, and *UNLOADT* - time spent to place the logs in a work cycle.

$$ETMT \text{ [s]} = ETRMT \text{ [s]} + ETFMT \text{ [s]} \quad (2)$$

Where:

ETMT - time spent during empty turn in a work cycle; *ETRMT*- time spent during empty turn rear movement in a work cycle, and *ETFMT*- time spent during empty turn forward movement in a work cycle.

$$LTMT \text{ [s]} = LTRMT \text{ [s]} + LTFMT \text{ [s]} \quad (3)$$

Where:

LTMT - time spent during loaded turn in a work cycle; *LTRMT*- time spent during loaded turn rear movement in a work cycle, and *LTFMT*- time spent during loaded turn forward movement in a work cycle.

Based on video analysis, the time spent in cleaning the work place (*CLEANT*) as well as the time consumed as delays were accounted separately. Cycle wise time consumption data, as well as the time consumption data characterizing the delays were summarized in a database developed in Microsoft Excel ®, where it was paired with records characterizing the date of acquisition, identification of a given work cycle, number of logs per work cycle, species of the logs composing a load, volume of the load (which was calculated in Microsoft Excel ®, based on the diameters and lengths of the logs), and fuel consumption. Data pairing was based on the information extracted from both the video files and field book. Statistical analysis was adapted to the recommendations given in [1] by developing the main descriptive statistics and by characterizing the share of elemental time consumption in the productive time. In addition, a Shapiro-Wilk test was implemented for the relevant variables to check the normality of data.

2.5.2. Movement speed and distance

The movement speed was estimated as the mean of GPS speed weighted by the number of observations falling in a specific speed category (*MMS*, m/s). For this purpose, the .gpx files were imported in the Garmin BaseCamp ® (https://www.garmin.com/ro-RO/software/basecamp/) software from where the information on location, heading, speed and time was exported into Microsoft Excel ® files (1104 observations), following a procedure which was similar to that from studies of [13-15]. Data on speed was first analyzed to detect and remove those observations indicating a speed of less than 0.5 km/h (0.14 m/s) [16], then the remaining data (1047 observations) was transformed from kilometers per hour in meters per second. Based on the refined dataset, the mean movement speed was computed by keeping all the speed categories extracted from Garmin

BaseCamp ®, and used to estimate the movement distances in the empty (*ETD*) and loaded (*LTD*) turns, as well as the average moving (*AMD*) distance according to **Equations 4-6**.

$$ETD\ [\mathrm{m}] = ETMT\ [\mathrm{s}] \times MMS\ [\mathrm{m/s}] \tag{4}$$

Where:

ETD - distance travelled during the empty turn; *ETMT* - time spent during empty turn in a work cycle, *MMS* - weighted mean movement speed.

$$LTD\ [\mathrm{m}] = LTMT\ [\mathrm{s}] \times MMS\ [\mathrm{m/s}] \tag{5}$$

Where:

LTD - distance travelled during the loaded turn; *LTMT* - time spent during loaded turn in a work cycle, *MMS* - weighted mean movement speed.

$$AMD\ [\mathrm{m}] = 0.5 \times (ETD\ [\mathrm{m}] + LTD\ [\mathrm{m}]) \tag{6}$$

Where:

AMD - average moving distance for a work cycle; *ETD* - distance travelled during the empty turn, and *LTD* - distance travelled during the loaded turn.

Statistical analysis related to the speed and movement distance included a normality check by a Shapiro-Wilk test, which was applied to the refined speed dataset followed by the estimation of relevant descriptive statistics to characterize the frequency of speed falling in a given category. In a third step, least square ordinary linear regression analysis was implemented to characterize the dependence relation between the work cycle time (*WCT*, s) and the average moving distance (*AMD*, m) which was estimated based on the weighted mean movement speed (*MMS*, m/s). The developed model was then used to model the work cycle time consumption with the aim of characterizing the productivity and fuel consumption functions.

2.5.3. Log volume, payload volume and production volume

Log volume (*LV*, m^3) estimates were obtained by using the Huber's formula based on field collected log biometrics. Then, the log volume estimates were used to compute the work cycle-based load volume (*PV*, m^3) as the sum of the volumes of component logs. The sum of loads' volumes was assimilated to the volume of production (*P*, m^3). Statistical analysis of load volumes aimed at checking for normality in data (Shapiro-Wilk test), characterizing the frequency of load volumes by considering the number of logs per loads and checking if there were contrasting differences in the load volumes as an effect of the number of logs per load. Most of these statistical steps included the development of histograms and graphs to characterize the mentioned distributions.

2.5.4. Fuel consumption

Fuel consumption estimates were aggregated in the form of hourly (*HFC*, l/h) and unit (*UFC*, l/m^3) fuel consumption by using the estimated production (*P*, m^3), engine running time (assimilated to productive time, *PT*) and the fuel consumption based on the repeated measurements taken in the field (*FC*, l), according to **Equations 7** and **8**.

$$HFC\ [\mathrm{l/h}] = FC\ [\mathrm{l}]\ /\ PT\ [\mathrm{h}] \tag{7}$$

Where:

HFC - hourly fuel consumption; *FC* - total fuel consumption as the sum of individual measurements taken in the field, and *PT* - productive time converted from seconds to hours.

$$UFC\ [\mathrm{l/m^3}] = FC\ [\mathrm{l}]\ /\ P\ [\mathrm{m^3}] \tag{8}$$

Where:

UFC - unit fuel consumption; *FC* - total fuel consumption as the sum of individual measurements taken in the field, and *P* - production as the sum of loads' volume.

The work cycle-based fuel consumption (*WCFC*, l) was related to average moving distance (*AMD*, m). For this purpose, the productive time of a work cycle (*WCPT*, h) and the global hourly fuel consumption (*HFC*, l/h) were used to estimate the fuel consumption (*WCFC*, l) for each of the observed work cycles (**Equation 9**), then the work cycle-based fuel consumption (*WCFC*, l) was modeled by a regression analysis as a function of average moving distance (*AMD*, m).

$$WCFC\ [\mathrm{l}] = WCPT\ [\mathrm{h}] \times HFC\ [\mathrm{l/h}] \tag{9}$$

Where:

WCFC - work cycle-based fuel consumption; *WCPT* - work cycle-based productive time, and *HFC* - hourly fuel consumption estimated by **Equation 7**.

$$WCUFC\ [\mathrm{l/m^3}] = WCFC\ [\mathrm{l}]\ /\ PV\ [\mathrm{m^3}] \tag{10}$$

Where:

WCUFC - work cycle-based unit fuel consumption; *WCPT* - work cycle-based productive time, and *PV* - load volume.

A similar linear model was developed to characterize the relation between the work cycle-based unit fuel consumption (*WCUFC*, l/m^3) and the average movement distance (*AMD*, m). To do so, the work cycle-based unit fuel consumption was calculated according to **Equation 10**.

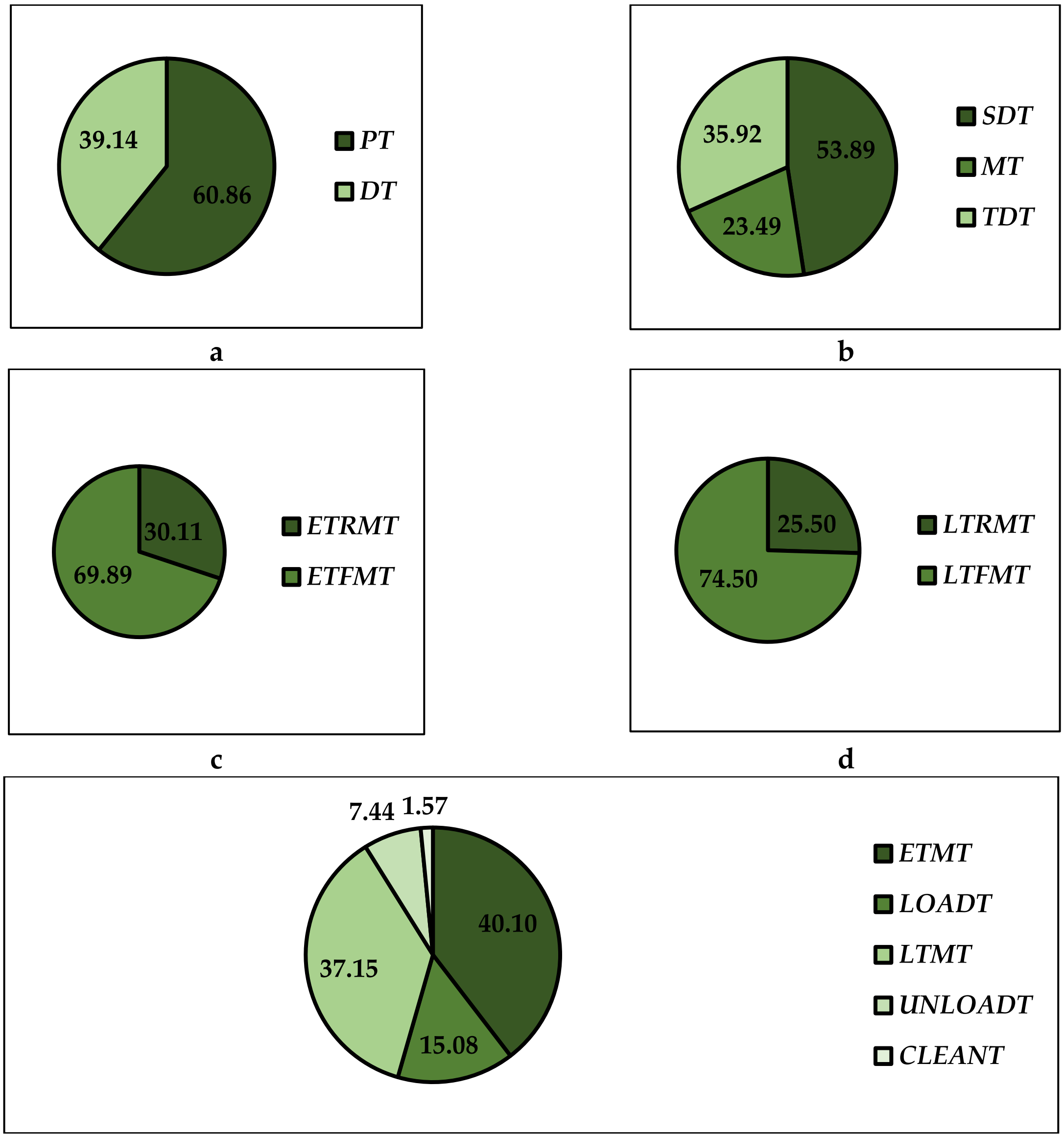
2.5.5. Efficiency and productivity

Similar to fuel consumption, efficiency and productivity of operations were first estimated for the average operational conditions. Estimates were reported both as gross and net figures where the net figures were estimated based on the productive time, whereas the gross figures were estimated based on all the observed time by excluding the delays caused by study. In a modeling approach, the productivity was related to the average movement distance by considering three scenarios. For all scenarios, the average movement distance (*AMD*, m) was estimated based on weighted mean speed and the time spent in work elements which included movement. Then, in the first scenario, the load volume (*PV*, m^3) and the work cycle-based productive time (*WCPT*, h) were used to estimate the productivity at the work cycle level, which was then related to the average movement distance (*AMD*, m). In a second scenario, the mean load volume was used instead of load volume to model productivity as a function of average movement distance (*AMD*, m). In the third scenario, the time consumption was modeled for a range of average movement distance from 1 to 300 m by the time consumption model developed as specified in **Section 2.5.2**, then the mean load volume and its standard deviation were used to estimate productivity in this range of movement distances. Mean load volume was used for productivity estimation while the productivity values computed by adding and subtracting the standard deviation were used to characterize the uncertainty in productivity estimates.

3. RESULTS

3.1. Time consumption

Figure 2 shows the share of time consumption categories in the total, delay and productive time. Productive time (*PT*) accounted for approximately 61% in the total observed time (**Figure 2a**), which was close to 16 hours.



a b c d e

Figure 2. Share of time consumption: a - productive time and delays; b - type of delays; c - share of rear and forward moving time in the empty turn time; d - share of rear and forward moving time in the loaded turn time; e - share of elemental time consumption in the productive time.

In the delay time (*DT*), the most important category was that of delays caused by study, which accounted for more than half as a result of making repeated measurements on the fuel consumption and biometrics of the operated logs (**Figure 2b**). Overall, the delay time accounted for 6.26 hours. In both, loaded and empty turns, the distribution of forward and rear moving time was similar (**Figure 2c,d**); rear movement accounted for approximately 30% in empty turn movement time (*ETMT*) and for approximately 26% in loaded turn movement time (*LTMT*). *ETMT* and *LTMT* had similar shares in the productive time (*PT*), accounting for approximately 40 and 37%, respectively (**Figure 2e**). Unloading time (*UNLOADT*) was approximately half of the loading time (*LOADT*) while clearing the workplace (*CLEART*) accounted for less than 2% in the productive time (**Figure 2e**). Detailed descriptive statistics on time consumption variables are given in **Table 2**.

Table 2. Descriptive statistics of time consumption

Time variable (Abbreviation, measurement unit)	Number of observations	Minimum value	Maximum value	Mean value ± Standard deviation	Median value	Sum
Total time (*TT*, s)	-	-	-	-	-	57637
Productive time (*PT*, s)	-	-	-	-	-	35079
Delay time (*DT*, s)	-	-	-	-	-	22558
Delays caused by study (*SDT*, s)	-	-	-	-	-	12157
Meal time (*MT*, s)	-	-	-	-	-	5299
Delays caused by technical reasons (*TDT*, s)	-	-	-	-	-	8102
Empty turn movement time (*ETMT*, s)	358	10	253	39.30±28.08	32.00	14068
Empty turn rear movement time (*ETRMT*, s)	358	3	43	11.83±6.44	10.00	4236
Empty turn forward movement time (*ETFMT*, s)	355	3	242	27.70±27.20	21.00	9832
Loading time (*LOADT*, s)	358	1	147	14.78±18.06	9.00	5290
Loaded turn movement time (*LTMT*, s)	358	10	110	36.40±20.21	29.00	13032
Loaded turn rear movement time (*LTRMT*, s)	356	2	28	9.33±5.08	8.00	3323
Loaded turn forward movement time (*LTFMT*, s)	357	2	87	27.20±18.22	21.00	9709
Unloading time (*UNLOADT*, s)	358	1	41	7.29±7.12	5.00	2609
Workplace cleaning time (*CLEANT*, s)	19	9	71	29.00±14.37	27.00	551
Work cycle time (*WCT*, s)	358	32	327	97.99±48.63	86.50	35079

As shown, a delay-free work cycle time accounted, on average, for approximately 98 seconds and it varied between 0.5 and 5.5 minutes. None of the variables on time consumption has passed the normality test. The mean and median values characterize the central tendency of time consumption for the repetitive work elements within a work cycle. Although the work place cleaning time accounted, on average, for close to 30 seconds (**Table 2**), its share in the productive time was low (**Figure 2e**) because it had the lowest occurrence in the observed time.

3.2. Load volume and production

In total, 816 logs with a dominant length of 4 m were counted during the field observation, of which 254 were of spruce and the rest (562) of silver fir. There was a dominance of loads containing 2 logs (**Figure 3**) and, by the number of logs, loads contained between 1 and 5 logs, averaging a number of 2.28±0.93 logs per turn. Production (*P*) observed during the study accounted for 600.84 m^3, and the load volume (*PV*, m^3) averaged 1.678±0.508 m^3.

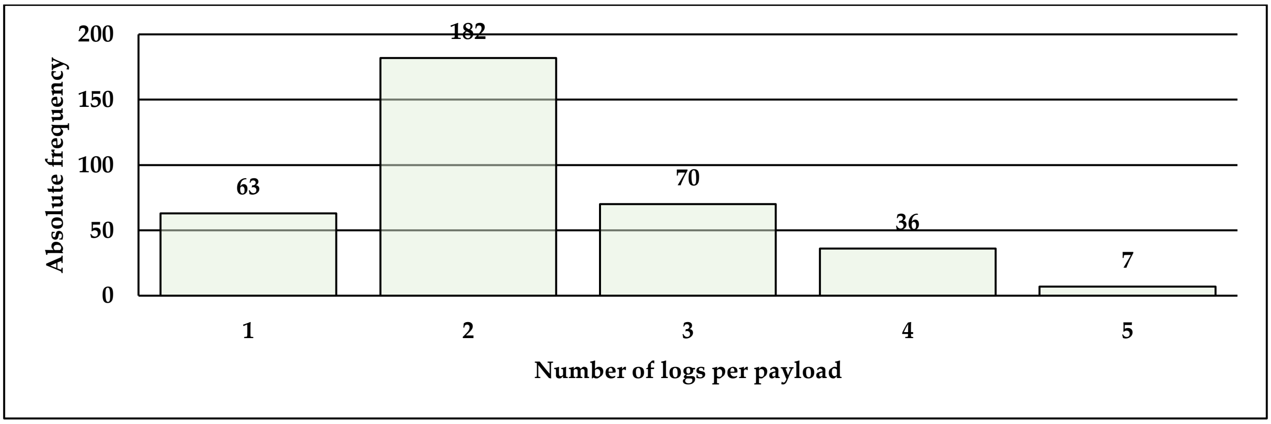
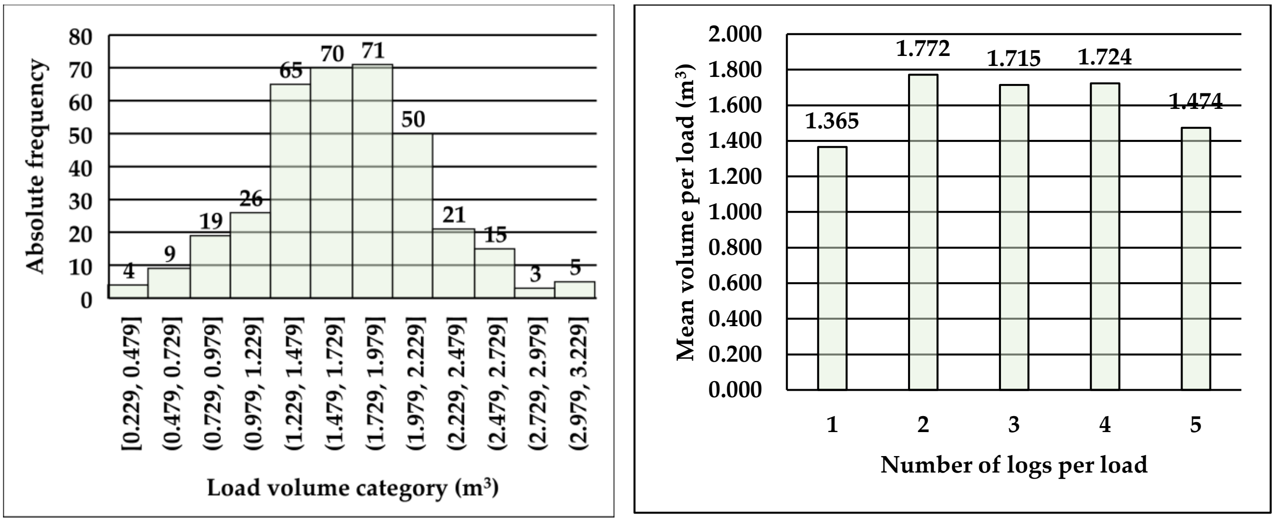


Figure 3. Absolute frequency of the loads by the number of contained logs



a b

Figure 4. Statistics of transported loads: a – histogram of load volume; b – mean volume in loads by the number of logs per turn.

Figure 4 shows the distributions of load volumes (**Figure 4a**) and of the mean volume in loads against the number of logs per turn (**Figure 4b**). Load volume was a variable that passed the normality test, while the mean volume of a load was close as value, irrespective of the number of logs per turn (**Figure 4b**).

3.3. Movement speed

As expected, the movement speed failed the normality test. Most probably this was due to a high frequency of movement speeds in lower speed classes as shown in **Figure 5**. By excluding the observations showing movement speeds less than 0.5 km/h, the refined dataset was characterized by movement speeds in between 0.5 and 11.0 km/h.

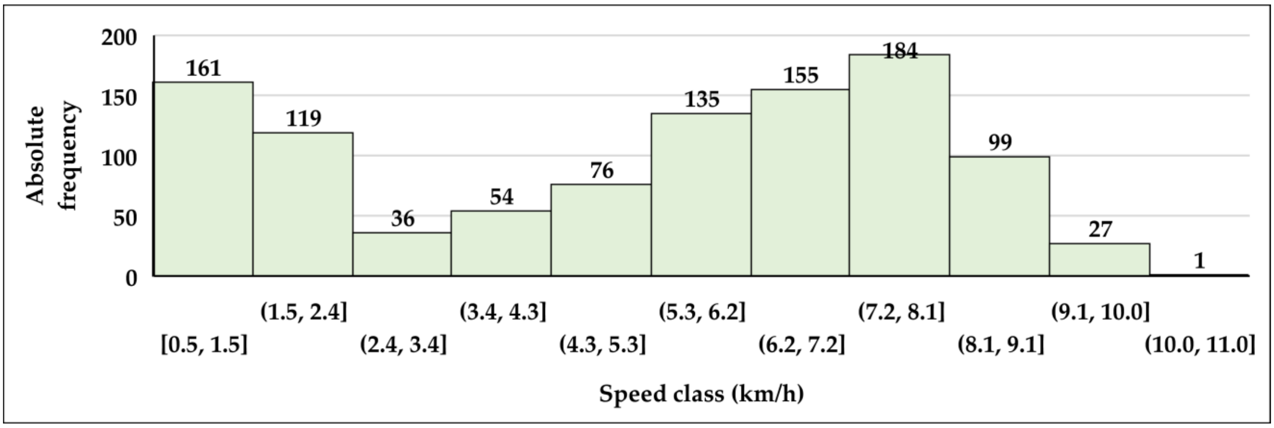


Figure 5. Absolute frequency of movement speed

In these conditions, the mean movement speed was estimated at 5.4 km/h while the weighted movement speed was estimated at 5.36 km/h (1.49 m/s). By the number of observations, dominant in the data set were speeds of up to 2.4 km/h, as well as speeds between 5.3 and 9.1 km/h which, together, accounted for more than 80% (**Figure 5**).

3.4. Work cycle time consumption model

The weighted movement speed (*MMD*, m/s) was used to estimate the empty, loaded and average moving distances by taking into consideration the time spent in these work elements (**Equations 4-6**). The model developed to relate the work cycle time (*WCT*, s) to the average movement distance (*AMD*, m) is shown in **Figure 6**.

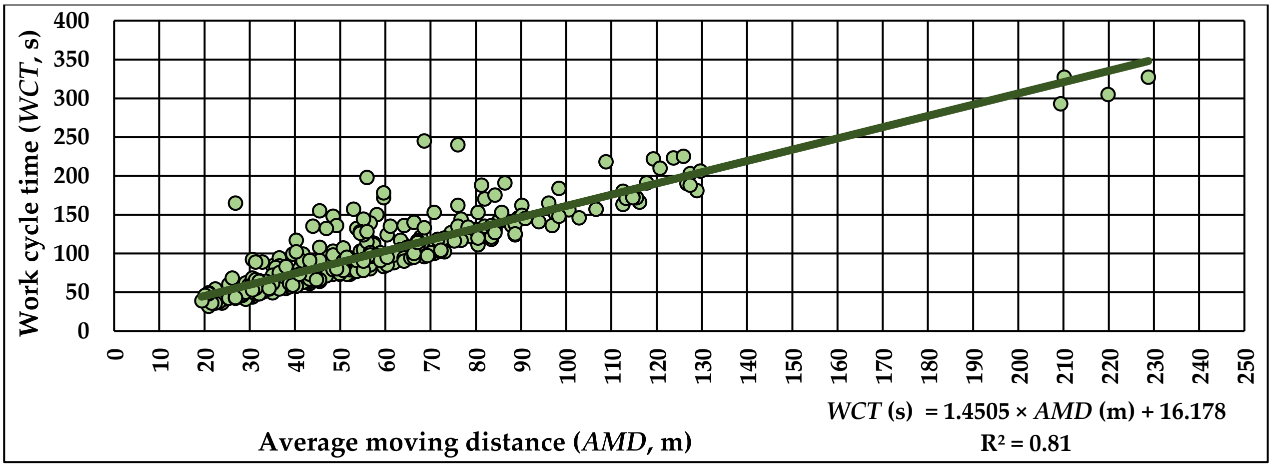


Figure 6. Dependence relation between the work cycle time (*WCT*, s) and the average movement distance (*AMD*, m).

The developed model explained the work cycle time (*WCT*, s) in a proportion of 81%, with the rest of variability being probably the effect of variability in loading and unloading time. The model was used for a part of the productivity assessment as a function of load volume and average movement distance (**Section 3.5**) by modeling the work cycle time consumption as a function of average movement distance and by using the mean load volume to plot the productivity estimates.

3.5. Efficiency and productivity

By considering the average operational conditions described in the materials and methods, as well as the statistics on time consumption and production, the estimates of efficiency and productivity are given in **Table 3**. As observed in this study, delays affected the efficiency and productivity to a significant extent, resulting in gross and net figures of productivity accounting for approximately 45 and 62 m^3/h, respectively (**Table 3**).

Table 3. Estimates of efficiency and productivity

Production (m^3)	Total time excluding delays caused by study (h)	Productive time (h)	Gross productivity (*GP*, m^3/h)	Net productivity (*NP*, m^3/h)	Gross efficiency (*GE*, h/m^3)	Net efficiency (*NE*, h/m^3)
600.84	13.47	9.74	44.62	61.66	0.022	0.016

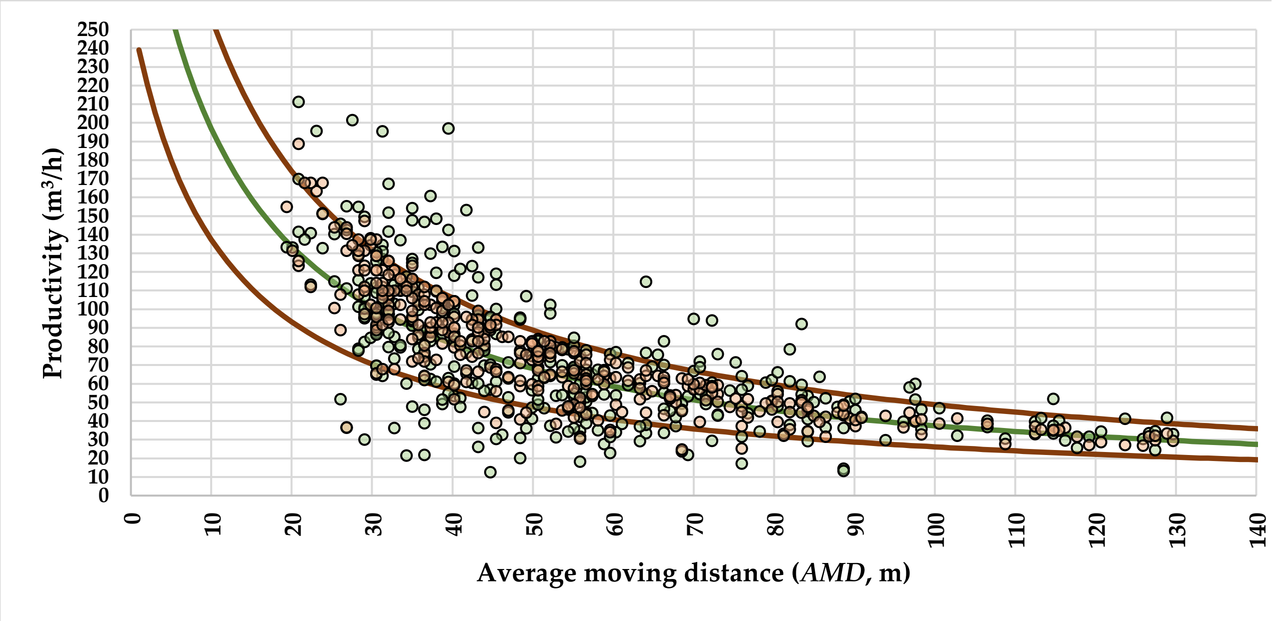


Figure 7. Productivity estimates. Legend: green dots stand for the experimental productivity computed for each work cycle based on load volume and work cycle time, brown dots stand for productivity estimates computed based on the mean load volume and the work cycle time, green line stands for the productivity estimated based on the mean load volume and the time estimated by model from Figure 6, and brown lines stand for upper and lower uncertainties of the productivity estimated by the green line by using as uncertainty measure the standard deviation of the mean load volume. Note: the figure excludes three observations in the range of *AMD* from 210 to 230 m.

Figure 7, on the other hand, shows the shape of productivity functions in relation to the average movement distance (*AMD*, m) by considering the three productivity estimation scenarios. In all scenarios, the productivity depended on *AMD* (which seemed to be the most relevant predictor), by power functions.

3.6. Fuel consumption

The global fuel consumption estimates which reflect the average working conditions are shown in **Table 4**. The total fuel consumption accounted during the field study was of 94.6 liters. Based on the productive time and the production estimates, the unit fuel consumption (*UFC*) was estimated at 0.157 l/m^3, while the hourly fuel consumption (*HFC*) was estimated at 9.7 l/h. **Figures 8** and **9** show the dependence relations between the work cycle-based fuel consumption (*WCFC*, l), unit fuel consumption (*WCUFC*, l/m^3) and the average movement distance (*AMD*, m).

Table 4. Estimates of fuel consumption

Production (m^3)	Productive time (h)	Total fuel consumption (*FC*, l)	Unit fuel consumption (*UFC*, l/m^3)	Hourly fuel consumption (*HFC*, l/h)
600.84	9.74	94.6	0.157	9.708

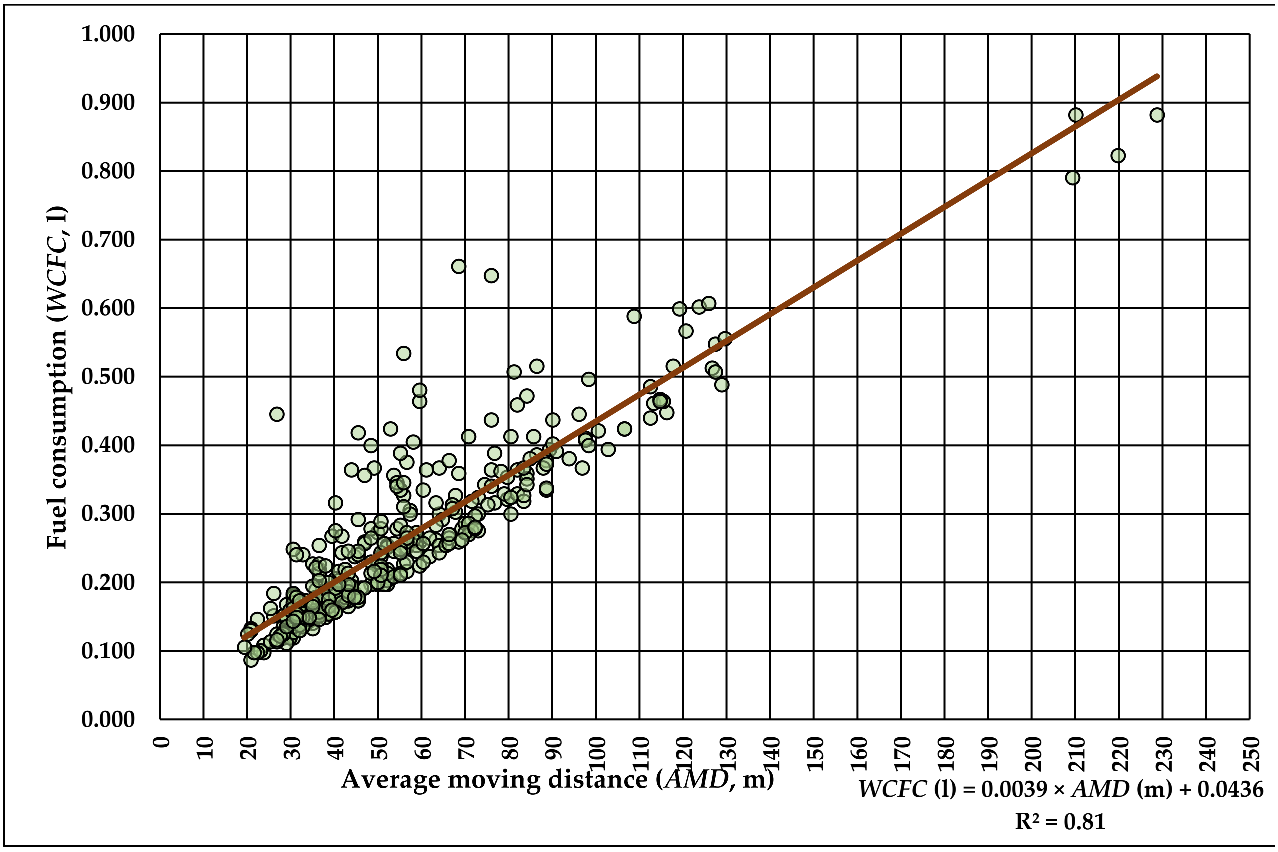


Figure 8. Dependence relation between work cycle-based fuel consumption (*WCFC*, l) and the average moving distance (*AMD*, m).

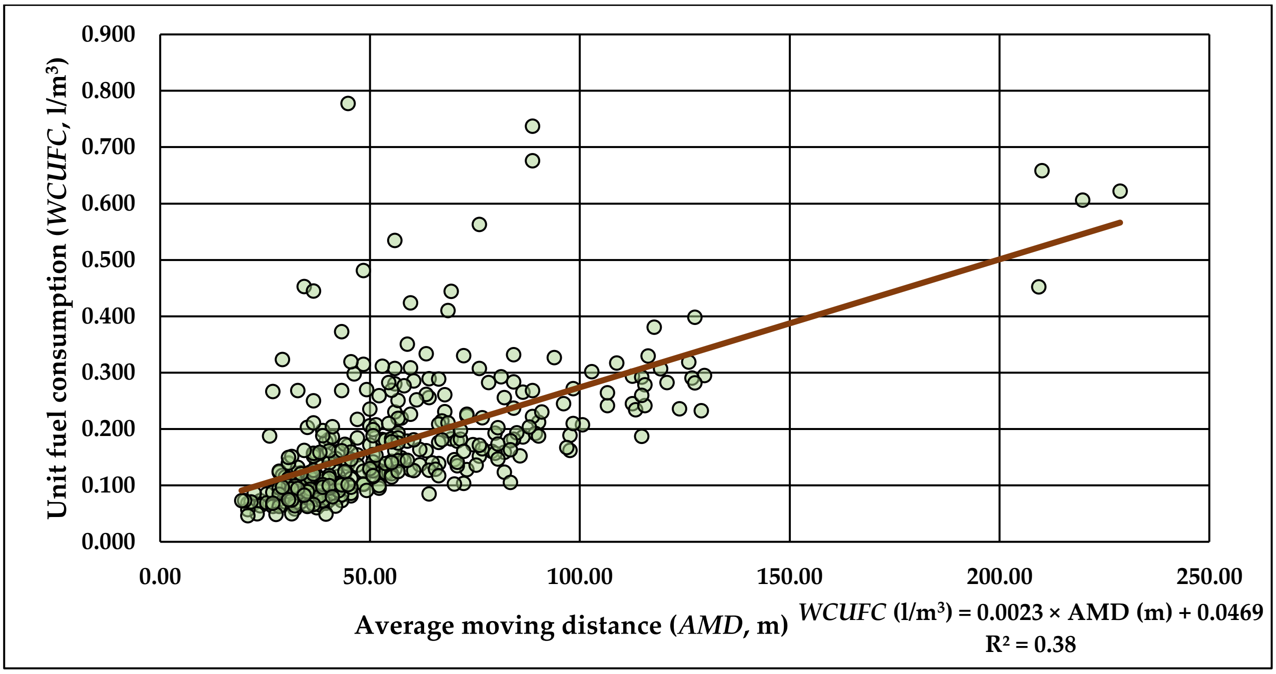


Figure 9. Dependence relation between the work cycle-based unit fuel consumption (*WCUFC*, l/m³) and the average moving distance (*AMD*, m).

4. DISCUSSION

Unfortunately, no studies were found to describe the operational performance of similar operations or machines and to provide data for comparison. However, the rate setting standards developed for older machines [8] may provide useful data for a rough comparison. **Figure A1** from the appendix section of this study plots the productivity rates of the mentioned standard against the center of operating distance categories, by considering the productivity modelled by this study. The mentioned standards set productivity rates which are differentiated by the species group and wood size category, placing the productivity of handling coniferous wood well apart from that of operating with broadleaved wood, at least for lower ranges of operational distances. It is worth to mention that productivity rates specified in [8] include other time categories such as preparing the machine for working, fueling the machine, starting and warming up the engine, and daily maintenance of the machine. The results of comparison (**Figure A1**) indicate a consistently high difference in productivity; it was higher in the case of the machine taken into study as opposed to the standardized rates, for all the range of operational distances taken into study. This does not come as a surprise since the newly-developed equipment is expected to perform better, including in maneuverability, but it cannot be explained by the biometrics of the logs, particularly their length, which is reflected in the load volume, and which was probably higher in the studies supporting the rate setting standards. Therefore, in the limits of handler's lifting capacity, the load per turn can be contrastingly higher, and will depend on the load size. The shape of productivity functions, on the other hand, are similar, with a higher decreasing trend of the productivity modeled by this study in the range of operational distances of up to 50 m, which may be due to the fact that the model of this study does not account for a fixed time for machine maintenance. Adding such a fixed maintenance time will lead to a drop in productivity as a function of operational distance. For instance, adding one hour of maintenance per operational day would drop the productivity rate from 180 to approximately 160 m^3/h for a distance of 12.5 m, and from approximately 16 to 14 m^3/h for a distance of 250 m.

A similar comparison may be made in terms of fuel consumption. For the average conditions of this study, which probably would reflect an average operating distance of approximately 250 m, the unit fuel consumption was estimated at 0.157 l/m^3 which, in standards described in [9], corresponds to a distance of close to 100 m. Similar to productivity, and accounting for improvements in the engine characteristics, the difference may rest in the size of the handled loads, which has changed in time from tree lengths to logs, at least for coniferous wood. In addition, the fuel consumption increases linearly by the operating distance, accounting for approximately 0.45 l for an average distance of 100 m, as shown in **Figure 8**. For an average load of approximately 1.6 m^3 (as of this study), at this distance, it will turn in a unit fuel consumption of approximately 0.28 l/m^3. Doubling the size of the payload (3.2 m^3) moved on the same distance, would mean a unit fuel consumption of 0.14 l/m^3, which is very close to the rates given in [9]. As a fact, the variability brought by the load size in unit fuel use can be seen in **Figure 9**, which describes a wide variation of this parameter for similar operating distances.

This study has some limitations which need to be accounted for. The most important one would be that of estimating the operating distances based on the GPS speed, a fact that may bring some uncertainty in part of the reported statistics and models. When affordable and feasible, the operating distances should be measured carefully and precisely in the field, which was not possible in this study since the logs were not moved in a specific order from given piles. On the other hand, the paths followed by the machine were not the same even in the case of moving the logs between two precisely placed piles. To this end, using the weighted speed to infer the operational distances based on the time consumption in machine moving tasks was the most reasonable approach, which can be validated by the shape of productivity functions shown in **Figure 7** and in **Figure A1**. In addition, there was a high difference between the experimental and modeled productivities, as shown in **Figure 7**. The experimental productivity reflects the variation in cycle wise loads which can be modelled by a power function to closely match the modeled productivity (data not shown herein). The same may be obtained for the productivity estimates based on the average payload, which will only overestimate the experimental productivity in lower ranges of operational distances (data not shown herein). Altogether, and by looking at the shapes of productivity functions shown in **Figure A1**, these indicate that the developed productivity models may stand for a correct approximation of the productivity as a function of operational distance.

5. CONCLUSIONS

The following conclusions may be drawn based on this study:

1. For the same operational distances, the productivity in log handling operations may depend largely on the load size which, in turn, would depend on the practices of log transportation operations. Since the current practice reflects the transportation of wood assortments at least for the coniferous wood, this will reflect negatively in the productivity of log handling operations in the log yards. However, it would be largely compensated by

the maneuverability brought by significant improvements in machine design, as shown by this study. In addition, improvements in productivity of log handling operations may be achieved by an economy of scale which may mean using bigger machines assuming that log sorting would be enabled and feasible in such scenarios. From this point of view, the machine taken into study may be seen as versatile in moving and placing the logs in the right piles;

2. A similar mechanism characterizes the fuel consumption which, although increases linearly, is affected by the load size when accounting for the unit fuel consumption metric. In addition to the load size, the operational distance stands for an important predictor of the unit fuel consumption;
3. The results of this study are descriptive and were not intended as productivity rates. To account for productivity rates, other fixed time categories such as machine maintenance and fueling need to be added in the estimation of productivity. By adding these categories, the productivity reported in this study will decrease for the same range of operational distances;
4. Caution should be used in interpreting the results of this study since some of the important predictors were estimated based on the GPS speed. This applies to the models developed to characterize the cycle time consumption, fuel consumption, unit fuel consumption and productivity as a function of the average movement distance.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

APPENDIX

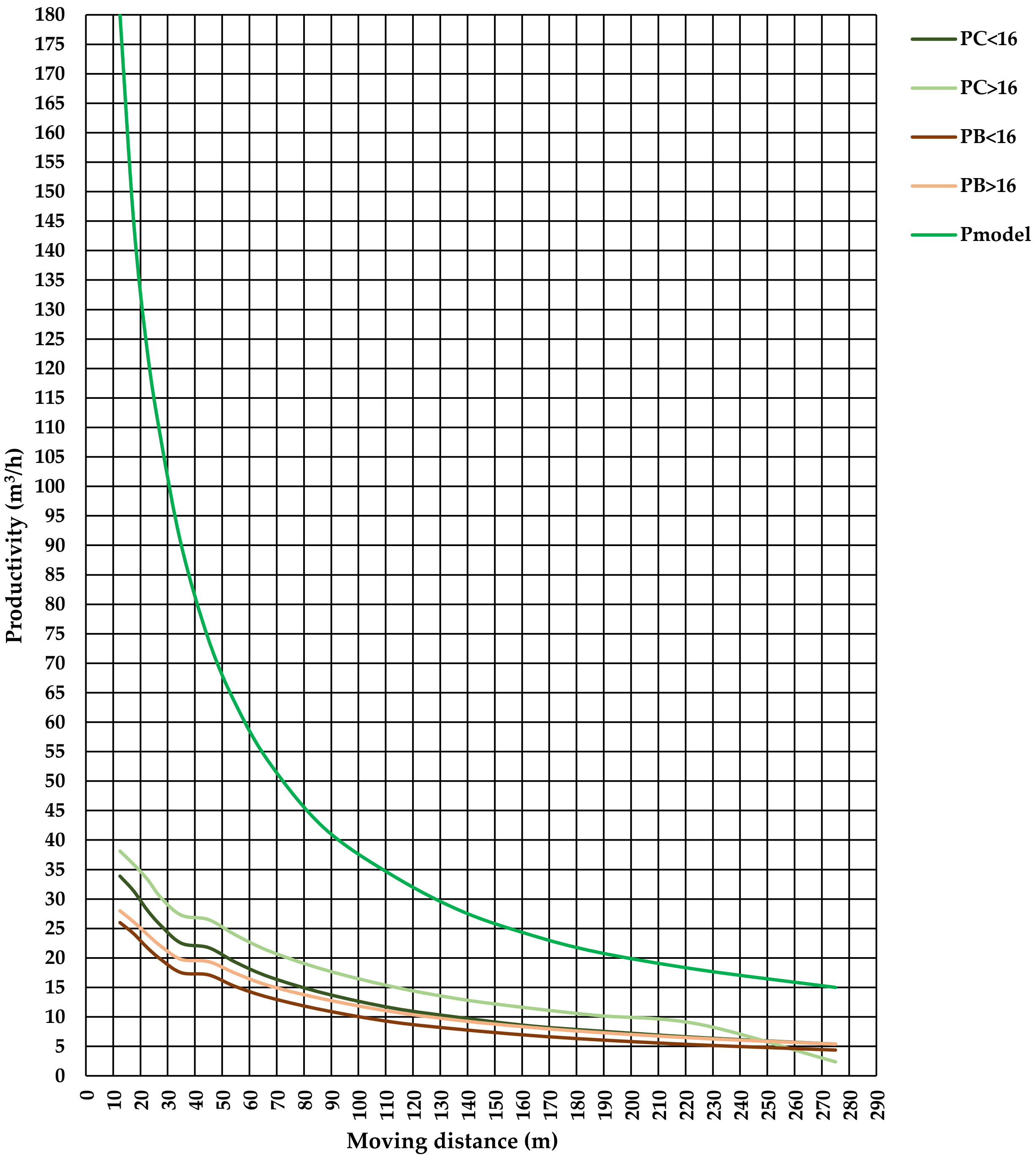

Figure A1. A comparison between the productivity rates (m^3/h) of the IFRON machine and the productivity modeled in this study. Legend: PC<16 - productivity rates of IFRON for coniferous wood with diameter lower than 16 cm, PC>16 - productivity rates of IFRON for coniferous wood with diameter higher than 16 cm, PB<16 - productivity rates of IFRON for broadleaved wood with diameter less than 16 cm, PB>16 - productivity rates of IFRON for broadleaved wood with diameter higher than 16 cm, Pmodel - productivity of Liebherr 451-13 machine as modeled by this study. Note: centers of the distance categories were used to plot productivity in the case of IFRON machine as specified in [8] for concrete paved ground.

EXTENDED ABSTRACT – REZUMAT EXTINS

Titlu în română: *Performanța utilajului Liebherr 451-13 în operaţii de manipulare şi stivuire a buștenilor.*

Introducere: *Evaluarea consumului de timp, carburant şi a productivității muncii reprezintă o componentă esențială a activității de exploatare a lemnului deoarece furnizează datele necesare pentru optimizare, elaborarea de norme de muncă, evaluarea costurilor şi evaluarea impactului operaţiilor forestiere asupra mediului. Astfel de evaluări se implementează sub forma studiului timpului concomitent cu cuantificarea producției realizate şi a consumului de carburanți. Deși literatura de specialitate abundă în studii care raportează date cu privire la performanța operaţională, nu există astfel de studii cu privire la utilajele moderne folosite în operaţii de sortat, manipulat şi stivuit lemn în depozite. Scopul acestui studiu a fost acela de a evalua consumul de timp, consumul de carburant şi productivitatea muncii în astfel de operaţii realizate cu un încărcător frontal Liebherr 451-13.*

Materiale şi metode: *Colectarea datelor s-a realizat în depozitul de lemn administrat de Ocolul Silvic Târgu Neamţ, pe durata a patru zile, între 23 şi 26 noiembrie 2021, prin utilizarea unei camere video pentru înregistrarea operaţiilor, a unei aplicaţii GPS pentru preluarea datelor necesare pentru estimarea vitezei de deplasare a utilajului, a unei rulete şi a unei clupe pentru măsurarea caracteristicilor biometrice ale buștenilor operați şi a unui cilindru gradat pentru măsurarea consumului de carburant. Având la bază un număr de 358 de cicluri de muncă, studiul descrie şi modelează consumul de timp în funcţie de distanța de operare estimată pe baza înregistrărilor GPS, estimează şi modelează consumul de carburant în funcţie de aceeaşi parametri şi, respectiv, estimează şi modelează productivitatea muncii. Estimările şi modelele au fost realizate prin tehnici ale statisticii descriptive şi prin utilizarea tehnicilor regresiei.*

Rezultate: *În total, în perioada colectării datelor de teren, au fost luate în studiu 816 piese de lemn, având lungimea dominantă de 4 m, care au fost deplasate pe distanțe cuprinse între circa 30 şi 500 m. Sarcina medie a fost compusă din 2.28 piese de lemn şi a avut un volum de 1.68 m^3. Pentru operaţiile luate în studiu, consumul de timp la nivelul unui ciclu de muncă depinde de distanța de operare. În aceste condiții productivitatea estimată prin excluderea diverselor tipuri de întreruperi a fost de 61.66 m^3/h şi a variat în funcţie de distanţa medie de deplasare a utilajului. Consumul unitar de carburant a fost estimat la 0.157 l/m^3 iar consumul orar de carburant a fost estimat la 9.7 l/h. Consumul de carburant a variat în funcţie de distanţa de operare.*

Discuții: *Rezultatele au fost comparate cu cele redate în normativele de muncă şi de consum pentru încărcătoare frontale de producţie românească. Productivitatea muncii a fost cu mult mai mare în cazul utilajului studiat, aspect ce poate fi explicat de manevrabilitatea mai bună a acestuia dar nu şi de dimensiunile pieselor şi a sarcinilor operate. Alura curbelor de productivitate a fost asemănătoare pentru cele două utilaje comparate, indicând faptul că rezultatele acestui studiu sunt valide. Mărimea sarcinilor operate este în măsură să influenţeze consumul unitar de carburant. Cu toate acestea, rezultatele trebuie interpretate cu precauție dat fiind faptul că distanțele de operare au fost estimate pe baza vitezei de deplasare înregistrată prin mijloace GPS.*

Concluzii: *Pentru distanțe de operare similare, productivitatea operaţiilor de manipulare şi stivuire a lemnului rotund poate să fie semnificativ influențată de mărimea sarcinilor operate, prin urmare de practicile curente adoptate în livrarea lemnului în depozite. Cu toate acestea, îmbunătățirile tehnologice aduse utilajelor pot compensa pierderile de productivitate cauzate de dimensiunile mai reduse ale pieselor de lemn şi sarcinilor printr-o manevrabilitate îmbunătățită. Un mecanism similar este aplicabil consumului unitar de carburant, care depinde de mărimea sarcinilor operate. Rezultatele acestui studiu sunt descriptive şi nu pot fi interpretate ca norme de muncă. Pentru elaborarea unor norme de muncă este necesară includerea altor categorii de consum de timp cum ar fi consumul de timp cauzat de mentenanța zilnică a utilajului.*

Cuvinte cheie: *utilaje moderne, manipularea şi stivuirea lemnului, consum de timp, consum de carburant, productivitate.*

REFERENCES

1. Acuna M., Bigot M., Guerra S., Hartsough B., Kanzian C., Kärhä K., Lindroos O., Magagnotti N., Roux S., Spinelli R., et al., 2012: Good Practice Guidelines for Biomass Production Studies; CNR IVALSA Sesto Fiorentino (National Research Council of Italy—Trees and Timber Institute): Sesto Fiorentino, Italy, 1-51, ISBN 978-88-901660-4-4.

2. Marchi E., Chung W., Visser R., Abbas D., Nordfjell T., Mederski P.S., McEwan A., Brink M., Laschi A., 2018: Sustainable forest operations (SFO): A new paradigm in a changing world and climate. Science of the Total Environment, 634, 1385-1397.
3. Borz S.A., 2014: Eficienţa în utilizare a ferăstraielor mecanice în operaţii de recoltare a lemnului – o sinteză a preocupărilor ştiinţifice naţionale şi internaţionale. Revista Pădurilor, 3-4, 80-96.
4. Borz S.A., 2015: A review of the Romanian and international practices in skidding operations. XIV World Forestry Congress, Durban, South Africa, 11p.
5. Spinelli R., Magagnotti N., Visser R., O'Neal B., 2021: A survey of skidder fleet of Central, Eastern and Southern Europe. European Journal of Forest Research, 140, 901-911.
6. Lindroos O., Cavalli R., 2016: Cable yarding productivity models: a systematic review over the period 2000–2011. International Journal of Forest Engineering, 27, 79-94.
7. Lundbäck M., Häggström C., Nordfjell T., 2021: Worldwide trends in methods for harvesting and extracting industrial roundwood. International Journal of Forest Engineering, 32, 202-2015.
8. Ministerul Industrializării Lemnului şi a Materialelor de Construcții, Centrala de Exploatare a Lemnului, Bucureşti, 1989: Norme şi normative de muncă unificate în exploatările forestiere, 491p.
9. Ministerul Economiei, Institutul Naţional al Lemnului, Bucureşti, 2009: Norme de consum specific. Lemn, combustibil, lubrifianți şi piese de schimb de mare uzură în activitatea de exploatare a lemnului, 121p.
10. Borz S.A., Marcu M.V., Cataldo M.F., 2021: Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. Croatian Journal of Forest Engineering, 42, 185-200.
11. Ignea G., Ghaffaryian M.R., Borz S.A., 2017: Impact of operational factors on fossil energy inputs in motor-manual tree felling and processing: results of two case studies. Annals of Forest Research, 60, 161-172.
12. Björheden R., Apel K., Shiba M., Thompson M.A., 1995: IUFRO Forest Work Study Nomenclature. Swedish University of Agricultural Science: Grapenberg, Sweden, 16p.
13. Borz S.A., Marcu M.V., Cataldo M.F., 2021: Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. Croatian Journal of Forest Engineering, 42, 185-200.
14. Borz S.A., Cheţa M., Bîrda M., Proto A.R., 2022: Classifying operational events in cable yarding by a machine learning application to GNSS-collected data: a case study on gravity-assisted downhill yarding. Bulletin of the Transilvania University of Braşov, Series II – Forestry – Wood Industry – Agricultural Food Engineering, 15(64), 13-32.
15. Cataldo M.F., Marcu M.V., Iordache E., Zimbalatti G., Proto A.R., Borz S.A., 2022: Performance of forwarding operations in biomass recovery from apple orchards. Small-Scale Forestry, 1-19. https://doi.org/10.1007/s11842-022-09500-4.
16. Bush C., Volk T.A., Eisenbies M.H., 2015: Planting rates and delays during the establishment of willow biomass crops. Biomass and Bioenergy 83, 290-296.