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Time Composition, Efficiency, Workload, and Noise Exposure during Tree Felling and Processing with Petrol and Battery-Powered Chainsaws in Mixed High Forest Stands

Anton Poje [1], Benjamin Lipužič [2], Ivan Bilobrk [3] and Zdravko Pandur [4,*]

[1] Department of Forestry and Renewable Resources, Biotechnical Faculty, University of Ljubljana, Večna Pot 83, 1000 Ljubljana, Slovenia; anton.poje@bf.uni-lj.si
[2] Slovenia Forest Service, Rožna Ulica 39, 1330 Kočevje, Slovenia; benjamin.lipuzic@zgs.si
[3] Subsidiary Zrinjevac, Zagreb Holding Ltd., Remetinečka Cesta 15, 10000 Zagreb, Croatia; ivan.bilobrk@zgh.hr
[4] Faculty of Forestry and Wood Technology, Institute of Forest Engineering, University of Zagreb, Svetošimunska Cesta 23, 10000 Zagreb, Croatia
* Correspondence: zpandur@sumfak.unizg.hr

Abstract: This study presents the effects of using a battery-powered chainsaw on work efficiency and ergonomics under real conditions during timber harvesting. The study was conducted during the felling and processing of coniferous and deciduous trees with a diameter at breast height (DBH) of 13 cm to 78 cm using both a petrol-powered and battery-powered chainsaw. The results include comparisons of time composition, work efficiency, psychophysical workload, and noise exposure. Heart rate and noise exposure were measured over ten days as part of a time study using the Husqvarna 543 XP petrol-powered chainsaw and the Husqvarna 540i HP battery-powered chainsaw. The comparison of the time composition between the chainsaws used showed 3%–4% differences in the duration of productive time operations and 16% in service time. The difference in work efficiency during the productive time between the two chainsaws was statistically insignificant, but generally higher when working with the battery-powered chainsaw than with the petrol-powered chainsaw. During the main productive time, the work efficiency was 9.89 min/t for the petrol-powered chainsaw and 9.44 min/t for the battery-powered chainsaw. The psychophysical workload of the feller was lower when using the battery-powered chainsaw than when using the petrol-powered chainsaw as the relative working heart rates during the entire productive time was 32.5% for the battery-powered chainsaw and 35.0% for the petrol-powered chainsaw. The noise exposure of the workers was lower when using a battery-powered chainsaw, namely 6.0 dB(A) and 0.4 dB(C) compared to the use of a petrol-powered chainsaw. The results of this paper indicate that battery-powered chainsaws can compete with petrol chainsaws in harvesting conditions that are currently considered unsuitable due to the large volume of trees.

Keywords: motor-manual work; feller; deciduous trees; coniferous trees; time study; heart rate; exposure to noise

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1. Introduction

Although forestry technology is rapidly evolving, chainsaws remain one of the most common tools used in forest work [1,2]. There are several reasons for this—typically, the scale of work is small, there is a lack of resources to invest in more expensive technology, and larger dimensions of wood primarily limit the use of CTL technologies. The most common reason for using a chainsaw lies in the terrain's characteristics, allowing for felling and processing wood solely with a chainsaw. Increasingly frequent natural disasters and the consequent rise in salvage cutting also create situations where chainsaws are used due to alterations in the physical wood properties and inaccessible terrains [3,4].

Among the main drawbacks of working with a petrol-powered chainsaw are the worker's exposure to noise, vibration, and exhaust fumes [4–8]. Despite technological advancements in chainsaws, logging work is still marked by the high workload, exposure to environmental factors, occupational diseases like hearing loss and vibration syndrome, and high frequency of accidents [4,9].

Battery-powered chainsaws present a good alternative to petrol-powered chainsaws as they are comparable in efficiency, ensure lower energy consumption, reduce the worker's exposure to noise and vibrations, and have a smaller negative impact on the environment [10–12]. Their potential is significant, but they require some additional improvements for regular implementation in forestry. The development of battery-powered chainsaws in forestry will escalate with the advancements in more powerful batteries, which currently remain a bottleneck for progress [10,13]. The chain sharpness is the most important factor affecting efficiency [14].

The workload of an arborist when working with a petrol-powered chainsaw is generally higher compared with using a battery-powered chainsaw [15]. Assessing the workload relies on heart rate during work, although it is essential to consider that heart rate is influenced by various factors such as the worker's psychological and health conditions or climatic factors [16].

The use of battery-powered chainsaws can bring changes in the work schedule and consequently alter the share of productive and unproductive time compared to the use of petrol-powered chainsaws. The composition of working time affects the logger, the environment, and the labor costs involved. With an optimal ratio of work phases, the logger is minimally exposed to vibration, noise, and workload while obtaining sufficient rest for maximum economic efficiency [17].

In contrast to previous studies, where battery-powered chainsaws were primarily used in young stands [10,12,16] or in urban areas [15], the objectives of this study were to compare (a) the time composition, (b) efficiency, (c) psychophysical workload, and (d) noise exposure when working with petrol and battery-powered chainsaws under real forest harvesting conditions. The objectives focused on the felling of coniferous and deciduous trees from the third (10 cm DBH) to the sixteenth (80 cm DBH) diameter class.

2. Materials and Methods

2.1. Study Locations

The study was conducted across three different work sites in Slovenia (Figure 1). The first work site was in the Kočevje Forest Management Area, Forest Management Unit Rog, within compartment 20B. The estimated timber stock in this compartment of 39.47 ha was 350 m^3/ha, consisting of 137 m^3/ha conifers and 213 m^3/ha deciduous trees. The predominant tree species were beech (56%) and fir (39%), with a small percentage of mountain maple (5%). The second work site was in the Novo Mesto Forest Management Area, Forest Management Unit Soteska, within compartment 38, on the northeastern slope of Pečka (910 m a.s.l.). The total area of this compartment is 23.77 ha, with a timber stock of 436 m^3/ha including 226 m^3/ha conifers and 210 m^3/ha deciduous trees. Beech (41%) dominates the timber stock, followed by spruce (27%) and fir (24%), with a small percentage of mountain maple (7%). The third work site was located in the Novo Mesto Forest Management Area, Forest Management Unit Poljane, within compartment 54, north of the peak Mali Rog (981 m a.s.l.). The estimated timber stock across 30.33 ha was 477 m^3/ha, with 177 m^3/ha conifers and 300 m^3/ha deciduous trees. Beech (49%) dominates the timber stock, followed by fir (20%) and spruce (17%), with a small portion of mountain maple (13%) (ZGS Viewer, 2022). Weather conditions during the recording period were favorable across all three sites, characterized by mostly sunny days without precipitation or strong winds. The terrain is relatively flat across all sites, with average slopes ranging from 10° to 17°.

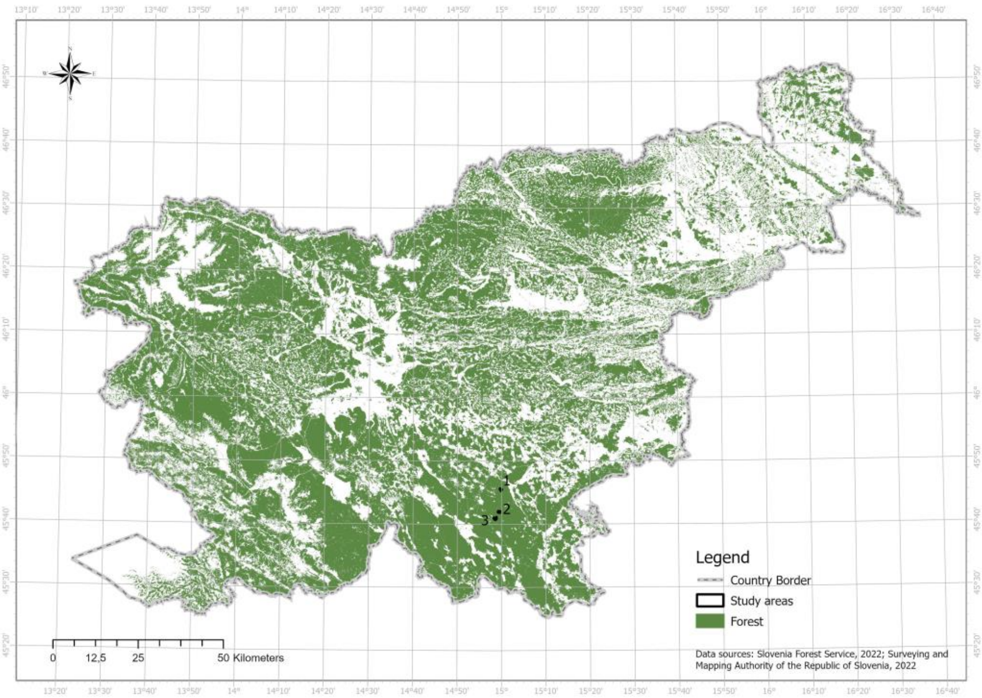

Figure 1. Location of the study work sites: **1** - Kočevje Forest Management Area, Forest Management Unit Rog, within compartment 20B; **2** - Novo Mesto Forest Management Area, Forest Management Unit Soteska, within compartment 38; **3** - Novo Mesto Forest Management Area, Forest Management Unit Poljane, within compartment 54.

2.2. Study Design, Worker, and Equipment Description

The entire research spanned eleven days, with one (first) day for testing the measurement procedures and ten days dedicated to recording the time study, volume of felled trees, workload, and exposure to noise during tree felling and processing.

During felling and processing with petrol and battery-powered chainsaws, coniferous and deciduous trees with a diameter in breast high (DBH) ranging from the third (10 cm) to sixteenth (80 cm) diameter class were selected. During each working day, one type of chainsaw was used for half of the day, and another type of chainsaw for the rest of the day. Random selection of the first type of chainsaw took place in the morning before the start of work by using a coin.

Measurements were conducted on one worker, specifically a feller involved in tree felling and wood extracting activities inside group work (two fellers and a tractor operator). To ensure accurate noise measurements, efforts were made to keep the fellers as far apart as possible. The worker was 38 years old, with a height of 176 cm, weight of 82 kg, and a body mass index of 26.5. The worker had no harmful habits like smoking or excessive alcohol consumption and also had 17 years of work experience, mainly in the role of a feller.

In this study, a petrol-powered chainsaw (543 XP) and a battery-powered chainsaw (540i XP), along with six Husqvarna BLi200X batteries (5 Ah) and a Husqvarna QC500 battery charger were used. Considering the weight of each battery (1.3 kg), six batteries were chosen (totaling 7.8 kg) to ensure a manageable load in the field, comparable to the petrol container a worker typically carries while using a petrol-powered chainsaw. The petrol-powered chainsaw weighed 4.5 kg without fuel and lubrication, had a cylinder displacement of 43.1 cm^3, and produced a maximum speed of 9600 RPM (Husqvarna, Stockholm, Sweden, 2022).

The battery-powered chainsaw, without the battery and the cutting equipment, weighed 2.9 kg, which was 1.6 kg lighter than the petrol-powered chainsaw without fuel, and cutting equipment weighing 4.5 kg. Considering similar cutting equipment and chains are used on both chainsaws, it was noted that even during operation, the battery-powered chainsaw (including the 1.3 kg battery and a full oil tank of 0.2 L) was 0.79 kg lighter than the petrol-powered chainsaw that was full fueled and also had oil tanks. At maximum power, the chain speed was comparable between the petrol-powered chainsaw at 24.6 m/s and the battery-powered one at 24 m/s. Similarly, the bar length was comparable with the petrol-powered chainsaw at 38 cm and the battery-powered chainsaw at 40 cm, while the chain pitch was identical at 0.325″.

2.3. Measurement Equipment Description

To measure the exposure to noise, a sound level meter (Bruel & Kjaer 2250, Nærum, Denmark) was fitted into a specially adapted backpack worn by the worker throughout the workday. A microphone (Bruel & Kjaer 4189, Nærum, Denmark) was attached to the protective helmet earmuff near the right ear and directed toward the chainsaw. Of all the recorded indicators, only two were used in the study: the maximum value of the C-weighted instantaneous sound pressure level or the peak sound level (LC_{peak} in dB(C)) and equivalent sound level (LA_{eq} in dB(A)). Both indicators were recorded every second (1 Hz).

To measure the psychophysical workload, a smart heart rate belt sensor by Suunto (Vantaa, Finland) was used. The heart rate during work was recorded in one-second intervals (1 Hz).

For the time study, continuous timing with a stopwatch was used. All recorded work operations were logged in a specific form designed for the time study. Time was measured to the nearest second.

In addition to the time study, the effects of work were also measured. The diameter at breast height (DBH) of the felled trees and the mean diameter under bark of individual assortments were measured using a tree caliper, to the nearest centimeter. For the purpose of the analyses, the DBH was changed into 5-cm thickness classes, where the first class included trees with a DBH of 10 to 15 cm. The length of assortments was measured using a logger’s tape, to the nearest centimeter.

2.4. Data Processing and Analysis

The data from the measurement devices were transferred to a computer using appropriate software and then input into MS Excel. Before incorporating the workload and noise exposure data into the collective dataset, visual inspection of all data was undertaken using graphs. For the workload data, evidently incorrect values of heart rate were eliminated such as sudden extremes (e.g., a value of 184) or very low heart rate values (value of 0). Regarding the noise level data, no errors were identified. After inputting the data into the dataset for all recorded values, the graphs were re-plotted. At this time, the success of synchronization with the time study was checked regarding previous research [18], where the heart rate and noise levels during work were higher during productive time and lower during delays. Upon visual inspection, the noise level pattern aligned with the time study that was observed, while there were more significant deviations in the heart rate pattern during work. Subsequently, sequences of heart rate data within certain days were excluded from further analyses.

Work efficiency was calculated using both chainsaws only for productive work time, since recording a full day of felling and processing with the battery-powered chainsaw was unfeasible due to a limited number of batteries. Consequently, periods of non-productive work such as meal breaks could not be solely attributed to a specific chainsaw type. Efficiency of time utilization was calculated as the ratio between the duration of each operation or productive work time and the mass of individual trees. Tree mass was computed from the volumes of individual assortments from the felled tree considering the density of roundwood in conifers and deciduous trees under bark (0.95 t/m^3, 1.1 t/m^3).

To calculate the workload indicator [18], the relative working heart rate (RHR%, Equation (1)), working heart rate (HR_w), rest (HR_{rest}), and maximum heart rate (HR_{max}) values were required. For HR_{rest}, the lowest measured value during the study of 41 beats per minute was assumed. HR_{max} was calculated as the difference between the value of 220 and the worker's age (38 years). Regarding previous studies [19], the *RHR*% during an 8-h work shift should not exceed 40%.

$$RHR(\%) = \frac{HR_w - HR_{rest}}{HR_{max} - HR_{rest}} \times 100 \quad (1)$$

To calculate the feller's exposure to noise during individual operations or relevant part of time (e.g., productive time), Equations (2) and (3) were used.

$$LA_{eq}\left(dB(A)\right) = 10 \times \log\left(\frac{1}{T}\sum(10^{0.1 \times L_i} \times t_i)\right) \quad (2)$$

T—cumulative time of exposure during relevant operation;
L_i–equivalent noise level in the *i*th interval;
t_i—the duration of exposure in the *i*th interval.

$$LC_{peak}\ \left(dB(C)\right) = maxLC_{peak_i} \quad (3)$$

LC_{peaki}—peak sound pressure level in the *i*th interval.

According to the EU Directive [20], the lower exposure action values were fixed at 80 dB(A) and 135 dB(C), the upper action values at 85 dB(A) and 137 dB(C), and the exposure limit values at 87 dB(A) or 140 dB(C) with respect to the equivalent sound level exposure level and peak sound pressure in an eight hour workday. Exceeding action and limit values result in measures to reduce noise exposure.

MS Excel® (v16.0, Microsoft, Redmond, WA, USA) was utilized for the data analysis and graphical representation of the results, and the JASP® program (v0.18.3, University of Amsterdam, The Netherlands) for statistical analysis. Each cycle or individual tree represented the statistical unit of the sample. Independent samples t-test and the Welch test were used alongside descriptive analysis to examine differences in the mean values among indicators. Regression analysis was employed to determine the relationship between two continuous variables and analysis of covariance (ANCOVA) to identify statistically significant differences between the mean values of the indicator after removing the influence of the dependent variable (the diameter class of the tree).

3. Results

In the analyses of the time composition, work efficiency, and exposure to noise, 115 trees were included, of which 52 trees were felled with a petrol-powered chainsaw, and 63 trees were felled with a battery-powered chainsaw. The overall average volume of the trees was 1.75 m^3, with an average total mass of 1.8 t. The average diameter of all felled trees in the study was 36.8 cm (37.4 cm for the petrol-powered chainsaw and 36.3 cm for the battery-powered chainsaw). The independent samples t-test revealed no statistically significant differences in the breast diameters for all trees felled with petrol-powered versus battery-powered chainsaws ($p = 0.743$) as well as for the conifers ($p = 0.437$) and deciduous trees ($p = 0.210$) individually.

3.1. Time Composition

The total measured workplace time in ten workdays took 55 h, 44 min, and 58 s. Within the workplace time, 43% constituted productive work time, 39% supportive work time, and 18% work-related delay time [21]. Since the design of the experiment did not allow for a comparison of the compositions of the total workplace time between the two considered chainsaws, only a comparison between the productive work time and parts of supportive work time and work-related delay time were analyzed.

The comparison of the composition of productive work time between the used chainsaws (Figure 2) revealed differences in the duration of operations, especially in the notch-, back-, and cross-cutting and delimbing. The notch-, back- and cross-cutting durations conducted with the battery-powered chainsaw were 3%–4% longer and delimbing was 3% shorter than that with the petrol-powered chainsaw. With detailed analysis including tree species, we found that the duration of forest protection measures (slash pilling, stump debarking) was 12% shorter with conifers than with deciduous trees. This result could be attributed to the fact that with conifers, the single tops are relatively quickly covered by branches, while with deciduous trees, due to their multi-topped and branched structure, the work is more time-consuming. Conversely, delimbing took longer when processing conifers with both types of chainsaws (8% longer when delimbing with the battery-powered and 6% longer with the petrol-powered chainsaw), which can be attributed to the higher level of branching in conifers compared to deciduous trees.

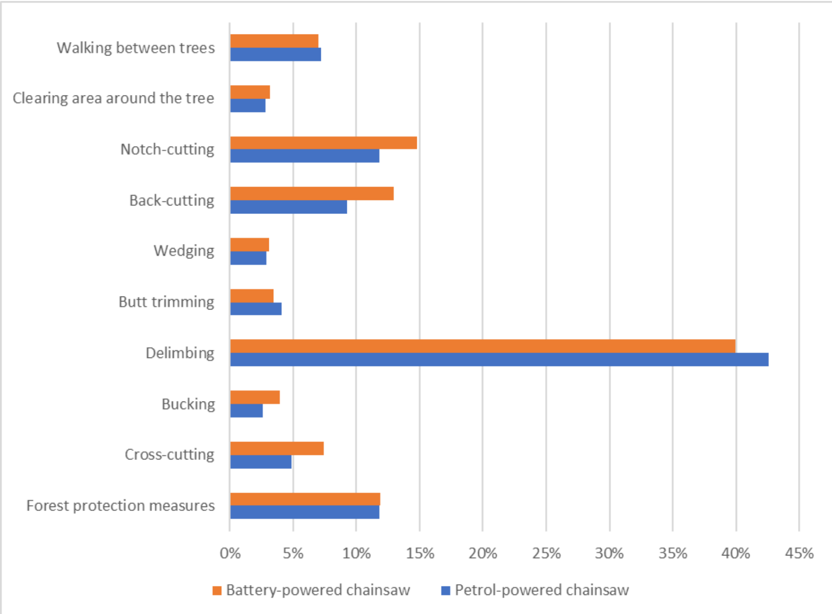

Figure 2. Comparison of the composition of productive work time when felling and processing with petrol-powered and battery-powered chainsaws.

The comparison of the parts of supportive work time and work-related delay time between the petrol-powered and battery-powered chainsaws (Figure 3) showed minor differences regarding personal breaks (2% more time with the petrol chainsaw), more substantial differences in ancillary work time related to work organization (14% more time with the petrol-powered chainsaw), and service time (16% more time with the battery-powered chainsaw). The results suggest that the type of chainsaw has a minimal impact on the personal breaks of the feller. Additionally, ancillary work time due to organization is either related to work planning or consultations with colleagues. Therefore, the higher percentage of ancillary work time with the petrol-powered chainsaw cannot be solely attributed to differences in work with different chainsaws. However, at least part of the difference in the use of time for equipment-related breaks can be attributed to the type of chainsaw. The reason for the higher percentage of equipment-related breaks when using the battery-powered chainsaw lies mainly in the time required for battery replacement. The worker replaces the batteries after they are completely drained and not before. With the petrol-powered chainsaw, refueling is more strategic and might be integrated into other tasks, partially explaining the higher percentage of time in ancillary work time and work-related delay time compared to the battery-powered chainsaw, which is typically undertaken less frequently than battery replacements in the case of the battery-powered chainsaws.

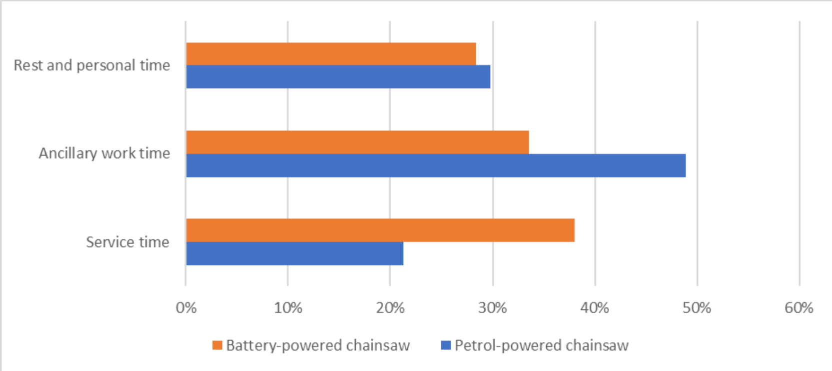

Figure 3. Comparison of the composition of parts of supportive work time and work-related delay time when felling and processing with petrol-powered and battery-powered chainsaws.

3.2. Work Efficiency

The average work efficiency ranged from 0.41 min/t in delimbing to 1.41 min/t in the operation of forest protection measures and from 0.44 min/t to 1.29 min/t when the battery-powered chainsaw was used. In operations of notch-, back-, and cross-cutting, the efficiency of the petrol-powered chainsaw was 6%, 22%, and 8% higher, respectively, and lower for 26% and 19% in operations of butt trimming and delimbing, respectively, compared to the battery-powered chainsaw. Despite the relatively large differences in work efficiency between chainsaws by individual operations, they were not statically significant. Work efficiency by all operations was significantly dependent on DBH class (Table 1).

Table 1. Statistical analysis of efficiency in operations of productive work time when working with petrol-powered and battery-powered chainsaws.

	Petrol-Powered Chainsaw			Battery-Powered Chainsaw			ANCOVA			
							Chainsaw Type		DBH Class	
Operation	**N (n)**	**A (min/t)**	**SD (min/t)**	**N (n)**	**A (min/t)**	**SD (min/t)**	**F**	***p***	**F**	***p***
Walking between trees	38	1.05	2.79	43	1.00	3.49	0.233	0.631	75.266	<0.001
Clearing area around the tree	27	0.53	2.88	33	0.52	2.84	1.428	0.237	42.732	<0.001
Notch-cutting	52	0.89	1.81	60	0.95	1.8	0.462	0.498	8.54	0.004
Back-cutting	44	0.79	1.69	61	1.01	1.8	3.107	0.081	31.89	<0.001
Wedging	28	0.41	2.39	24	0.53	3.02	0.386	0.537	27.41	<0.001
Butt trimming	29	0.44	2.16	26	0.35	1.89	2.246	0.14	16.009	<0.001
Delimbing	51	3.63	1.76	62	3.04	1.96	3.745	0.056	34.673	<0.001
Bucking	33	0.51	2.62	52	0.44	2.56	3.769	0.056	32.762	<0.001
Cross-cutting	42	0.48	2.13	53	0.52	2.13	0.277	0.6	8.271	0.005
Forest protection measures	41	1.41	3.18	54	1.29	3.88	0.072	0.789	93.743	<0.001
Productive work time	52	9.89	1.79	63	9.44	2.08	0.539	0.464	77.653	<0.001

Legend: N—number of trees, A—average, SD—standard deviation, F—F-statistics, *p*—*p*-value.

Time consumption per ton of wood during productive work time when using both chainsaws significantly decreased with increasing DBH class (Figure 4). The efficiency of the petrol-powered chainsaw in productive work time was lower than that of the battery-powered chainsaw. Work efficiency was significantly dependent on DBH class and not statically significant between chainsaws. The average work efficiency during productive work time was 9.89 min/t when using the petrol-powered chainsaw and was 5% lower compared to the battery-powered chainsaw (Table 1).

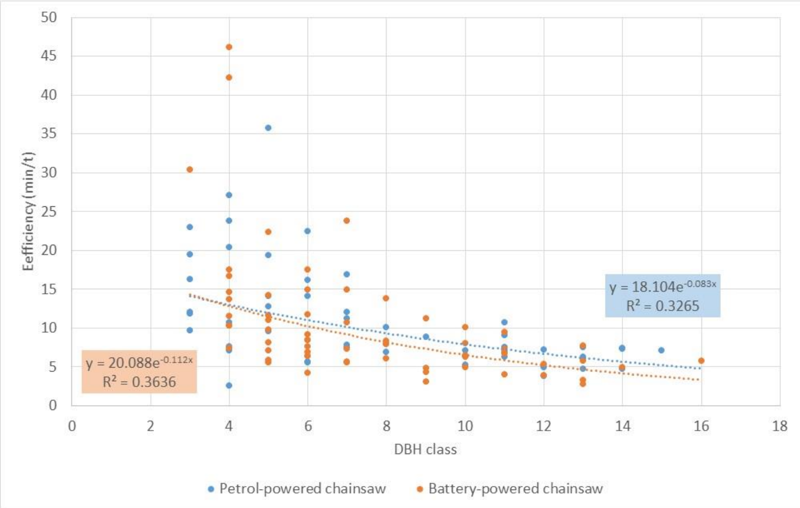

Figure 4. The dependence of efficiency on the DBH class of the tree for productive work time.

3.3. Psychophysical Workload

The psychophysical workload analysis included 13 trees felled with the petrol-powered chainsaw and 29 trees felled with the battery-powered chainsaw. Trees were felled during 7 days (the fourth, fifth, and eighth days were entirely excluded). The average diameter of the selected trees was 40.2 cm, with a total average volume of 2.35 m^3 and an overall average mass of 2.4 t. On average, the DBH of the trees included in the petrol-powered chainsaw sample was 14 cm larger (49 cm) than those felled using the battery-powered chainsaw (35 cm). The independent samples t-test, assuming unequal variances, indicated statistically significant differences in the average DBH between the selected trees felled with the battery-powered and petrol-powered chainsaws ($p = 0.014$).

Heart rates during measurements (one-second intervals) ranged from 41 bpm to 153 bpm recorded during delays and during back-cutting. The working heart rate (HR_W) and relative working heart (RHR%) during productive work time were 90.4 bpm and 35.0% for the petrol-powered chainsaw and 86.9 bpm and 32.5% for the battery-powered chainsaw, respectively. In productive work time, the highest workload was measured during wedging, where an ax was used, and the lowest during walking between trees. Operations such as back-cutting and butt trimming have also proven to be high psychophysically demanding operations. The workload was higher when working with the petrol-powered chainsaw in all operations of productive work time, except for wedging and butt trimming. The wedging operation was the only operation were the RHR% exceeded the threshold of 40% (Table 2).

Table 2. Workload during felling and processing with petrol-powered and battery-powered chainsaws in operations of productive work time.

Chainsaw Type	Petrol-Powered Chainsaw			Battery-Powered Chainsaw		
Operation	T (min)	HR_W (bpm)	RHR (%)	T (min)	HR_W (bpm)	RHR (%)
Walking between trees	11.48	82.1	29.2	35.32	81.7	28.8
Clearing area around the tree	9.60	93.1	36.9	11.67	85.9	31.8
Notch-cutting	45.82	86.7	32.4	71.05	86.1	32.0
Back-cutting	34.87	92.9	36.8	55.5	90.7	35.3

Wedging	11.28	100.6	42.2	17.22	102.1	43.3
Butt trimming	16.10	90.6	35.2	18.18	91.0	35.5
Delimbing	146.08	91.5	35.8	200.03	86.6	32.3
Bucking	10.22	92.0	36.2	19.00	89.4	34.3
Cross-cutting	17.47	86.2	32.0	38.55	83.6	30.2
Forest protection measures	18.57	86.3	32.2	58.3	83.7	30.3
Productive work time	321.48	90.4	35.0	524.82	86.9	32.5

Legend: T—measurement duration, HR_W—working heart rate, RHR—relative working heart rate.

From the graph (Figure 5), it is evident that the working heart rate in productive work time increased with the DBH class of trees, particularly when using the petrol-powered chainsaw compared to the battery-powered one. The workload was higher when using the petrol-powered chainsaw than the battery-powered one. A covariance analysis (ANCOVA) revealed statistically significant differences in workload between the chainsaw types ($p < 0.001$) and demonstrated that workload was significantly correlated with the DBH class of felled trees ($p = 0.004$). This result proves that the observed differences in the workload when using the two considered chainsaws (Table 2) did not originate from a different sample of trees.

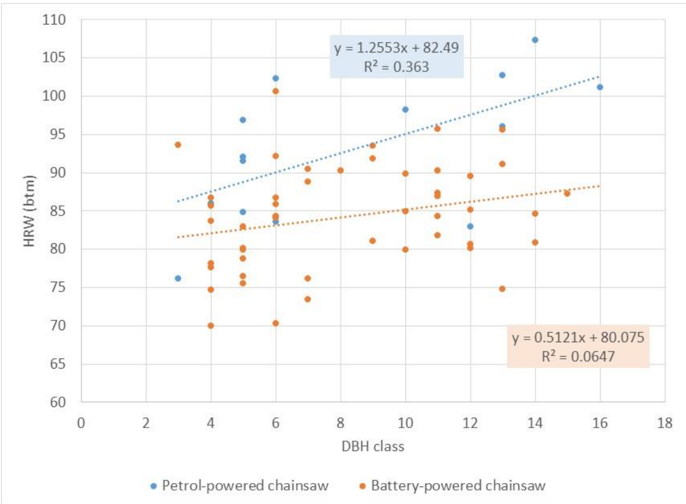

Figure 5. The dependence of working heart rate in productive work time on DBH class.

According to the results, workload during productive work time increased with the cycle sequence when using the petrol-powered chainsaw and decreased when using the battery-powered chainsaw (Figure 6). However, the dependency on cycle sequence within the analysis of covariance was not found to be significant ($p = 0.484$). On the contrary, workload during productive time when using the petrol-powered chainsaw was significantly higher ($p < 0.001$) compared to the battery-powered saw. The results revealed that the workload was more or less constant during workdays, and that there was no evident fatigue accumulation.

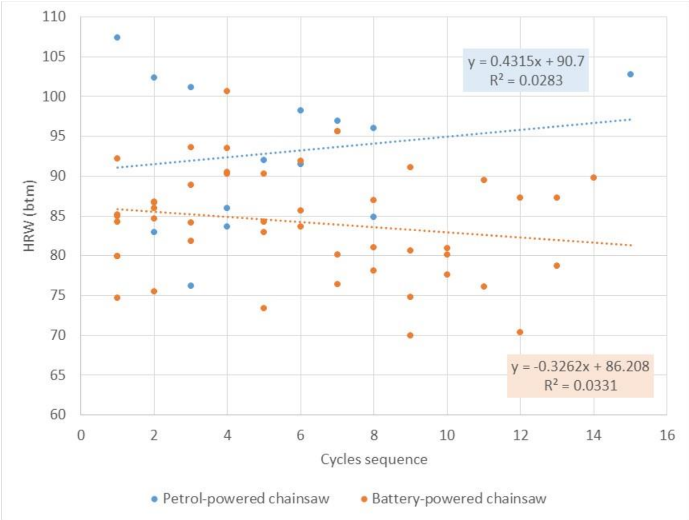

Figure 6. The dependence of the working heart rate in productive work time from the cycle sequence.

3.4. Exposure to Noise

The highest second-by-second LAeq noise level was recorded during the wedging operation carried out with an axe (109.2 dB(A)), while the lowest (22.7 dB(A)) occurred during the ancillary work time related to work organization. The highest second-by-second LCpeak noise level was measured during the wedging operation (140.1 dB(C)) and the lowest during rest and personal time (38.6 dB(C)).

The noise exposure during productive work time when using the battery-powered chainsaw was 139.7 dB(C) and 90.8 dB(A) and was 0.4 dB(C) and 6.0 dB(A) lower compared to using the petrol-powered chainsaw (Table 3). Comparing these results with the thresholds from the EU Directive [20], it can be observed that both the lower and upper exposure action values were exceeded during productive work time, regardless of the chainsaw used. Additionally, in the absence of ear protection (ear muffs or ear plugs), the exposure limit values were also exceeded.

Table 3. Statistical analysis of noise exposure after productive time operations when working with petrol-powered and battery-powered chainsaws.

Chainsaw Type	**Petrol-Powered Chainsaw**			**Battery-Powered Chainsaw**		
Operation	**T (min)**	**LC_{peak} (dB(C))**	**LA_{eq} (dB(A))**	**T (min)**	**LC_{peak} (dB(C))**	**LA_{eq} (dB(A))**
Walking between trees	49.37	122.5	84.1	48.13	120.2	80.9
Clearing area around the tree	19.53	120.5	94.2	21.93	121.7	87.5
Notch-cutting	81.68	123.9	99.4	101.45	132.7	91.4
Back-cutting	64.20	136.2	99.2	89.07	136.2	91.1
Wedging	19.98	140.1	95.9	21.13	139.7	95.4
Butt trimming	27.83	120.7	97.7	23.48	128.0	89.5
Delimbing	292.48	134.4	96.7	274.75	126.6	91.1
Bucking	17.63	121.1	95.3	26.95	123.8	89.8
Cross-cutting	33.57	134.2	96.9	51.13	136.1	90.0
Forest protection measures	82.95	131.5	93.8	81.87	120.9	90.7
Productive work time	689.23	140.1	96.9	739.9	139.7	90.8

Legend: T—measurement duration, LC_{peak}—peak sound level, LA_{eq}—equivalent sound level.

The differences in the LC_{peak} noise levels between the used chainsaws were not unambiguous. When using the battery-powered chainsaw, the LC_{peak} noise levels were lower in operations walking between trees (2.3 dB(C)), wedging (0.4 dB(C)), delimbing (7.8 dB(C)), and forest protection measures (10.6 dB(C)), equal in back-cutting, and higher in the operations of clearing area around the tree (1.2 dB(C)), notch-cutting (8.8 dB(C)), butt trimming (7.3 dB(C)), bucking (2.7 dB(C)), and cross-cutting (1.9 dB(C)) compared to the petrol-powered chainsaw.

In contrast to the LC_{peak} noise levels, the LA_{eq} noise levels were 0.5 to 8.2 dB(A) lower in all operations when using the battery-powered chainsaw than those of the petrol-powered chainsaw (Table 3). The operations with the most significant differences included notch-cutting (7.9 dB(A)), back-cutting (8.1 dB(A)), and butt trimming (8.2 dB(A)).

4. Discussion

4.1. Time Composition

The ratio between productive and non-productive time affected the psychophysical workload, exposure of forest workers to the risks arising from physical agents, and consequently, work efficiency. During workplace time, 43% of the time was measured as productive work time and 57% as supportive and non-work time (non-productive time). The results are consistent with the findings in previous research [18], where during the final felling and processing of conifers, 61% of the recorded work time was productive, while 39% was non-productive work time.

In general, when using the battery-powered chainsaw, the largest part of productive work time was dedicated to the operation of delimbing (40%), followed by notch-cutting (15%), back-cutting (13%), and forest protection measures (12%). Additionally, according to previous research, when using a Stihl MS 220 C-B battery-powered chainsaw, delimbing took the longest out of all the productive work time operations [22]. The duration of specific working operations primarily depends on the working conditions. Factors such as the diameter at breast height (DBH), steam volume and length, and the degree of branching significantly influence the time composition during felling and processing, consequently affecting the feller's exposure, as observed by Poje [9]. The composition of time during work is also influenced by the psychophysical fitness of the feller and their work experience.

When comparing the composition of time between the two saws used in the research, when working with the battery-powered chainsaw 3%–4% more time was needed to perform notch-, back-, and cross-cutting (i.e., operations where the saw is most heavily loaded). Since the chain on both saws was identical, we assumed that the differences were due to the different rotation speed of the chain when cutting under full load, which was most affected by the power of the chainsaw engine. On the other hand, faster work with a battery-powered saw when delimbing could be attributed to the smaller weight and slimmer design of the battery-powered chainsaw.

The study highlighted potential differences in the time composition of non-productive time, where the battery replacement in the battery-powered chainsaw might lead to varying service time durations.

4.2. Work Efficiency

Work efficiency is a crucial metric from several perspectives—economic, organizational, and ergonomic. It helps determine the time required to produce a unit of the final product, directly impacting the workload of the worker. For most working operations during productive work time, the efficiency of the battery-operated chainsaw was higher than that of the petrol-powered chainsaw. Previous studies [10,13,14] have observed that the work efficiency with petrol-powered chainsaws is higher compared to battery-operated ones. They primarily attribute this to the lower engine power and reduced chain rotation speed of battery-powered chainsaws. Chain sharpness, a factor not examined in this study, is believed to play a significant role in cutting time and battery consumption [14]. Consistent with the findings of previous research [17], the time consumption (in minutes per ton) for both chainsaws significantly decreased with increasing DBH, regardless of the operation.

For a fair comparison of work efficiency, it's essential to compare efficiency at equal DBH of felled trees. In this study, the work efficiency at DBH of 35 cm during productive work time was 8.8 min/t with a battery-powered chainsaw and 9.9 min/t with a petrol-powered chainsaw. Considering the non-productive time factor (quotient between non-productive time and productive time) equal to 2.33 [9] and the same for both chainsaws, the work efficiency during productive work time at a felled tree's breast diameter of 35 cm was 20.1 min/t for the battery-powered chainsaw and 23.2 min/t for the petrol-powered chainsaw. Poje [9] found the efficiency with a more powerful petrol-powered chainsaw (Stihl 361 C BQ) and the same non-productive time factor to be approximately 14.25 min/tree at a DBH of 35 cm, indicating lower efficiency in our study. Vranešič [23] measured work efficiency during productive work time in hardwood stands with a Husqvarna 372 XP petrol-powered chainsaw at DBH of 16 cm equal to 16.6 min/t. At the same DBH value the efficiency in our study is higher for both petrol-powered (13.51 min/t) and battery-powered chainsaws (13.79 min/t). Jereb [11] found an average efficiency during spruce felling and processing at an average felled tree DBH of 19 cm. In productive work time it was 13.32 min/t for a Husqvarna 445 petrol-powered chainsaw and 26.4 min/t for three different battery-powered chainsaws combined (Husqvarna 536 LiXP (Stockholm, Sweden), Stihl MSA 200 C (Waiblingen, Germany), and Makita DUC 353 Z (Anjo, Japan)). Thus, work efficiency during productive work time with both petrol-powered and battery-powered chainsaws in this study at the same diameter is slightly higher (12.80 min/t, 12.88 min/t), with a more significant difference for battery-powered chainsaws.

Comparisons with previous research indicate that work with the battery-powered and petrol-powered chainsaw used in our study is generally comparable or even more efficient for trees with smaller DBH compared to more powerful chainsaws typically used in professional settings, which are more effective for larger DBH. However, comparing efficiency between studies is challenging due to various factors (worker, study duration, site characteristics, etc.) significantly influencing efficiency and varying across studies.

In the study, we indirectly determine that 10 to 12 full batteries are required for an 8-h working day when felling with a battery-powered chainsaw, which is 1 to 4 batteries more than found in previous studies [24]. We assume that the differences in the number of batteries required are mainly due to the differences in the DBH of the felled trees.

4.3. Psychophysical Workload

As an indicator, the resting heart rate shows both the health risk and the physical fitness of a person. A normal resting heart rate is between 50 and 90 beats per minute [25] and is lower in physically active people than in physically inactive people. The resting heart rate is mainly reduced by endurance activities [26]. For example, the resting heart rate of top athletes in endurance sports is between 35 bpm and 40 bpm [27]. The low value of the resting heart rate of the worker included in this study indicates his high level of physical fitness. As a result, physical fitness influenced the values of working heart rate as well as the values of relative heart rate, which were lower than in previous studies [9,18,28]. Considering that the workload was highest during productive work time [9,18], we estimated that the average value of relative heart rate during an eight hour working day did not exceed the threshold value of 40% [6], regardless of the saw used.

The workload was found to be lower when working with a battery-powered chainsaw than when working with a petrol-powered chainsaw, both for the total productive work time and for the vast majority of productive work operations. We assumed that the lower workload was due to the lower weight and slimmer design of the battery-powered chainsaw. The workload during work operations was consistent with previous studies [9], and was generally the highest during felling operations due to the active use of an ax when driving wedges and the stooped posture, which have been shown to affect workload [29]. In addition to the highest workload, wedging is also problematic in terms of vibration exposure [30].

As expected, the workload during the productive work time increased significantly with a larger DBH, as felling and processing larger trees is more physically strenuous. The workload increases with larger trees because of the actual physical strain and not because of the duration of the task [9]. The workload did not increase during the entire work shift, which indicates that the workload (work pace and organization) was well-designed from an ergonomic point of view.

4.4. Noise Exposure

Exposure to noise when working with the petrol-powered chainsaw was lower than in previous studies using more powerful professional chainsaws [31], but comparable to studies using smaller professional chainsaws [10]. The results of our study therefore show that noise exposure is strongly influenced by the power of the chainsaw.

The noise level while using the battery-powered chainsaw during productive work time was lower compared to using the petrol-powered chainsaw. The difference of 6.0 dB(A) and 0.4 dB(C) between the noise levels when working with the battery-powered and petrol-powered chainsaws was smaller than that found in previous research (14.5 dB(A)) [10], which might be due to the type of chainsaw used. Despite the lower LC_{peak} exposure when using a battery-powered chainsaw, the exposures during some operations of the effective working time were unexpectedly higher, namely by 8.8 dB(C) during notch cutting, by 7.3 dB(C) in butt trimming, and by 1.9 dB(C) in cross-cutting compared to the petrol-powered chainsaw. The results thus show how important long-term and accurate measurements are, as individual isolated events such as impacts can also influence the exposure to noise. The calculation of the average LC_{peak} noise levels, together with previous studies [10], showed that the LC_{peak} exposures when using a battery saw were lower than when using a petrol saw for all operations of productive work time. In contrast to the LC_{peak} exposures, the LA_{eq} exposures were lower during all productive time operations when using the battery-powered chainsaw, which is consistent with previous studies [10].

In comparison with the EU Directive [20], the noise exposure when using a battery-powered chainsaw during the entire productivity work time exceeded the lower action values (80 dB(A) and 135 dB(C)) during the entire productive work time. The upper action values and the exposure limit values were also exceeded for all work processes during productive working hours, with the exception of walking between the trees. Since the validation of the results only applied to an eight hour work day, we estimate that the lower and upper exposure action values, according to the exposure indicator LC_{peak}, are exceeded when hearing protection is used continuously (SNR of 20 dB to 30 dB) during felling and processing with a battery-powered chainsaw. The same applies to the exposure indicator LA_{eq}, as the noise exposure during the non-productive time is generally lower than during the productive time [17], and the non-productive time is less than 355 min in a 480-minute working day. This amount of time would be needed to reduce the noise exposure during the working day to below 85 dB(A), based on the very conservative estimate that the noise exposure during non-productive time is 60 dB(A), which is the approximate sound level of a conversation between two people [17].

Based on the results, using battery-powered chainsaws may impose less noise pollution on the environment compared to using petrol-powered chainsaws, which is particularly important during arboricultural measures in urban settings or near quiet zones (https://www.ecologic.eu/sites/default/files/publication/2023/50034-species-protection-rules-under-the-birds-and-habitats-forestry-country-studies.pdf, accessed on 16 January 2024) of individual animal species such as the capercaillie or white-tailed eagle.

5. Conclusions

The main conclusions of the study, in which petrol and battery-powered chainsaws were used for felling and processing in mixed high stands and under real forest harvesting conditions, are:

- The use of a battery-powered chainsaw has relatively little impact on the composition of productive time, but a greater impact on the composition of non-productive time, as more time is needed for maintenance;
- The work efficiency in productive time and productive time operations with a battery-powered chainsaw is not statistically significantly different from that of a petrol-powered chainsaw;
- The psychophysical workload when using a battery-powered chainsaw is lower than when using a petrol-powered chainsaw;
- The noise exposure during productive time is lower when using a battery-powered chainsaw than when using a petrol-powered chainsaw.

The clear message of this study is that battery-powered chainsaws can compete with petrol chainsaws, even in harvesting conditions that are currently considered unsuitable for use due to the large volume of trees, and even outperform them in terms of ergonomics.

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