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Processing Small-Sized Trees at Landing by a Double-Grip Machine: A Case Study on Productivity, Cardiovascular Workload and Exposure to Noise

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Abstract: To be characterized as sustainable, forest operations need to be studied and validated from many points of view, including their productivity, ergonomics and costs. In most of these areas, performance enhancement was found to be sustained by the development and use of mechanization, including that of landing operations done to process small-sized trees. For these, an affordable and sustainable alternative could be that of using double-grip processors. However, there is a lack of information characterizing their capability and performance, which was one of the main reasons for carrying on this study. Observational data were collected over four operational days for a HYPRO 775 double-grip processor to estimate the productivity, exposure to noise and cardio-vascular workload in processing small-sized trees at landing. Miniaturized dataloggers and video recording were used to document close to 28 h spent at the workplace and 15 h of operation, respectively. A time study was used to estimate the productive performance and the commonly used metrics were computed to evaluate the exposure to noise and cardio-vascular workload. A delay-free work cycle was framed around a processed tree and it took, on average, ca. 45 s. Based on 901 processed trees (average height of ca. 12 m and average breast height diameter of ca. 12 cm), the net productivity rate was estimated at ca. 65 trees per hour (ca. 224 logs of 2.4 m produced per hour). While the cardiovascular activity indicated light work, exposure to noise seems to be a concerning problem to be addressed in the future, given the figures found (A-weighted sound pressure level higher than 85 dB(A) and the sound pressure level normalized for a nominal day of 92.79 dB(A)). This becomes even more important as this study found a machine utilization rate of ca. 60%, therefore an extension of productive time could increase the exposure to noise. We conclude that double-grip processors represent a valuable technical alternative in processing small-sized trees at landing if supplementary precautions would be taken against exposure to noise. These may rest very well in the awareness and behavior of the operators as well as in wearing protective equipment.

Keywords: sustainability; mechanization; harvesting; thinning; performance; operations; evaluation; improvement; awareness; protective equipment

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1. Introduction

Sustainability of forest operations is included in the current scientific discourse, being often studied by the approach of balancing their productivity, operational costs, environmental impact and ergonomics, to name just few of the currently described scientific areas in the related sciences [1,2]. It is commonly agreed that the increment of operational performance has been enabled by the development of mechanization in operations [3]; it has been further enhanced by the introduction of innovative and modern machines [4,5], decisively contributing to the improvement of operational sustainability.

Transition from motor-manual to mechanized tree felling and processing operations is, perhaps, one of the most beneficial advancements in forest operations mechanization.

It has contributed to a productivity increment, especially in selective cuts in which a high number of logs are to be recovered from a given tree [6], and to the ergonomics and safety of the workers [7,8], which are known to be far poorer in the case of motor-manual operations [3,9,10]. Nonetheless, the mechanization level of tree processing operations varies widely in different regions of the world [6,11]. In turn, this limits the use of some harvesting methods, generally shaping a situation for which sound solutions need to be developed [12].

In terms of costs, ergonomics, labor availability, safety, time consumption and productivity, selective thinning operations deployed in young and dense forests could be problematic, especially when the removal intensities are low and a substantial motor-manual tree processing is required at the felling site [3,12]. This was often seen as a good reason to move labor-intensive manual operations from the felling site to the landing [3]. A typical option is to use the full tree harvesting method, according to which the trees are felled and extracted to the landing without any further processing in the forest. At the landing, tree processing into logs (i.e., delimbing and bucking) can be done much easier either by using chainsaws [3] or mechanized equipment [13].

Several studies have been carried out in different parts of the world to check the performance of single-grip harvesters and processors in forest operations, with the aim to provide an informed ground on equipment capabilities as a baseline for its selection and use in operations, performance modelling and cost estimation [13–19]. Recently, important steps were taken to improve our understanding on the human-machine interaction [20], fine-scale performance of process mechanics [21] and human exposure to harmful factors [22]. However, mechanized tree processing at the landing was less addressed by scientific studies, and work organization and operational environment in such work places are different from those typically found in the forest stands. While various machine types could be used for such operations [3], a potential solution for small- and very small-sized trees and low removal intensities could be the use of double-grip processors. The equipment concept itself is not new as it has been described by some textbooks [3] and studied in some older scientific articles such as that dealing with tree felling and processing into the forest [23]. Nevertheless, pursuing the idea of using double-grip processors for landing operations may be worth the effort, as the work put in the development of mechanization has shown a huge potential for improvement by flexible, cost-affordable solutions embodied in the harvesting equipment [5]. In addition, examining the productivity and ergonomics of harvesting equipment is typically the first step taken to understand its behavior in relation to different operational environments [1] and to adapt it to human capability, as a prerequisite to find the best fitting solutions [2]. Also, the rationale of implementing performance assessment studies is strongly related to the limited information and applicability of the international productivity models and statistics to a given area [24], as well as to our current ability to obtain more accurate and a more profound understanding of operational performance by the use of modern technology [25,26]. To the best of our knowledge, no recent studies were done to evaluate the performance of double-grip processors working at landing, a reason for which the authors of this paper have carried out a check study [27], concluding that more research is still needed to obtain finer and more accurate data on their performance. As approached by many of the recent studies given before, the main parameters to evaluate are not only the productive performance but also the operational sustainability from an ergonomics point of view.

The goal of this work was to check and validate the benefits and drawbacks of using a double-grip processor to fully mechanize the processing operations of small-sized trees at landing, which was enabled by the introduction of such equipment at least in the harvesting operations deployed in the planted forests of Ecuador, where the data supporting this study was collected. To do so, the approach of the study, by its objectives, was twofold. A first objective were to evaluate the performance of tree processing operations done at the landing by the means of a detailed time-and-motion study and by accounting for the main productivity metrics. The second objective of the study was to evaluate the main conditions related to the ergonomics of operations. Since the mechanized operations done by processors are more prone to the exposure to noise and to the stress caused by a highly repetitive focus-demanding work, the parameters taken into study were the exposure to noise and cardio-vascular workload.

2. Materials and Methods

2.1. Study Area, Harvesting System and Work Organization

The study area is located near the Cotopaxi volcano (Ecuador) at ca. S0° 41.632′–W78° 34.907′, 3200 m.a.s.l., in a planted forest (Figure 1C,D) which is managed by the company Aglomerados Cotopaxi, featuring different ages and species such as those from the *Pinus* and *Eucalyptus* genera. In the locations taken into the study (Figure 1C,D), the forests were established using Monterey pine (*P. radiata* D. Don), and they were scheduled for selective thinning operations which were implemented in 2018, by the means of the harvesting system described in Figure 1A. At the study date, the forest stands chosen for field observation were 9-years old. According to the data provided by the holding company they were characterized by a mean height of ca. 12 m and a mean diameter at the breast height of ca. 12 cm. The implemented harvesting system (Figure 1A), which is typical for thinning operations in the area, supposed a motor-manual tree felling followed by the extraction using a farm tractor equipped with a winch; at the landing, processing operations were undertaken by a double-grip HYPRO 775 processor (Figure 1B) powered by a Massey Ferguson tractor (model 4921, featuring an engine output of 77 kW and a closed cabin).

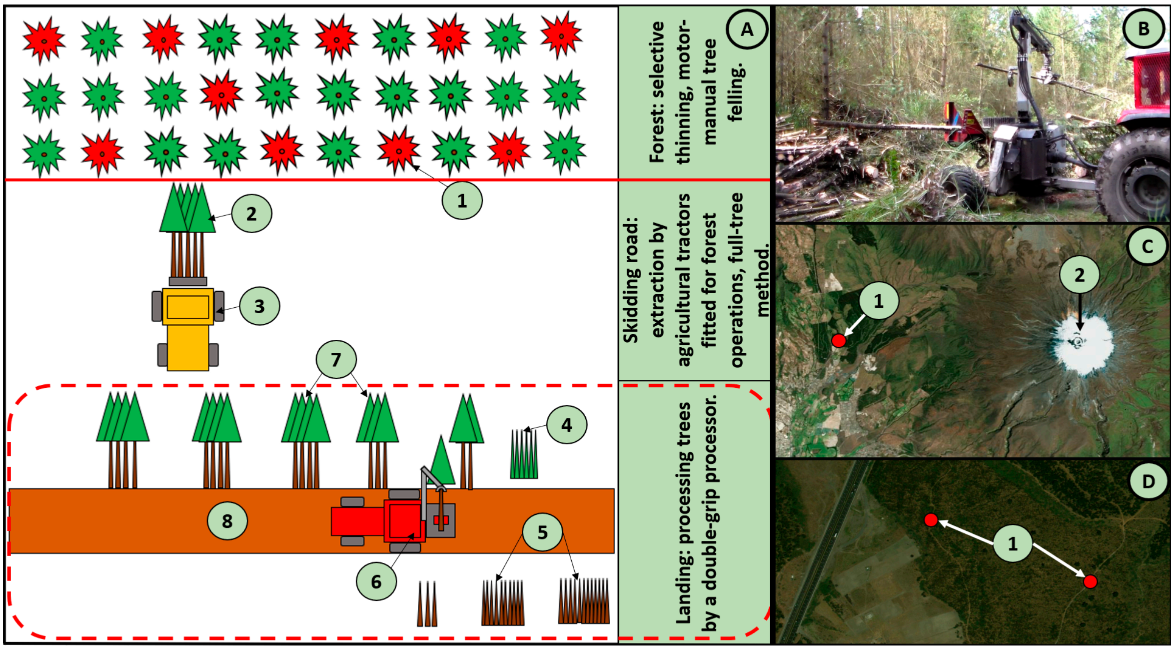

Figure 1. Study location, description of the harvesting system and study's scope. Legend: A—harvesting system and operation taken into study: 1—tree removed by selective thinning, 2—bunch of trees skidded to landing, 3—farm tractor used for skidding, 4—pile of tops and limbs, 5—wood pile, 6—double-grip processor, 7—bunches of trees to be processed, 8—road; B—HYPRO 775 double-grip processor observed in this study; C—general study location: 1—location of the surveyed operations, 2—Cotopaxi volcano; D—locations of operation: 1—points of observation (landings).

Tree processing operations, which were observed in two locations, were done by the same operator, who was accustomed with the machine on which he has previously worked in the same forests. The main characteristics of the processor taken into study are given in detail in [27,28]. It enables tree loading by the means of a crane, gripping by the rollers and knives mounted on the horizontal frame, feeding of the trees to delimb them by the means of the knives, as well as some degrees of frame movement. The operation of the machine was done from within the cab and the processed logs were exhausted directly in piles with no or few assistances from the crane. It is worth mentioning here that the wood coming from thinning operations is typically used by Aglomerados Cotopaxi to build boards and wooden mouldings [29]; during our study, the logs were bucked to a length as close as possible to the requirements of the following operations, which include the transportation to the milling facility by the means of trucks. As such, the average length of the logs was rated at ca. 2.4 m and there were no requirements for advanced, more sophisticated equipment for log grading tasks.

The typical work consisted of driving the machine to the operation places (landings) and between them, followed by tree processing. However, there were few machine movements to these workplaces and between them during the observation and they were removed from analysis; as such, only the tasks that took place at the landings were observed and included in the analysis. These consisted of movements of the machine between the tree bunches to be processed, loading trees into the processor, processing, removing the slash from the processor, piling tops and processing slash and, occasionally, arranging the logs in piles and the trees in bunches. The company and the operator were informed about the goals of the study, and they agreed to participate. The operator has verbally approved wearing observation devices and being observed, and he was instructed to carry on his tasks in his usual way of doing the work.

2.2. Data Collection

Data collection was done in four days, from 9th to 12ve of May 2018, by the means of a small video camera which was mounted on a tripod, an Extech® 407760 sound pressure level datalogger (Extech Instruments, FLIR Commercial Systems Inc., Nashua, NH, USA), a Polar V800 (Polar, Kempele, Finland, www.polar.fi, accessed on 15 December 2020) heart rate sampling device, and an Extech® VB300 accelerometer (Extech Instruments, FLIR Commercial Systems Inc., Nashua, NH, USA). Even though the heart rate sampler includes a GPS unit, to be able to document the events in which the operator was outside the cab, an external GPS unit (GPSmap 62stc, Garmin International Inc., Olathe, KS, USA) was placed on the cab of the machine to permanently monitor its location.

Video camera was set to continuously record media files and it was placed each time at a convenient distance from the observed machine to cover in the field of view the operations surveyed. Once the work was completed in a given location and the machine progressed to access new wood bunches, the camera was moved and placed in the new location accordingly. Field data was collected as media files of 20 min in length each (some files recorded at the end of given operational days were shorter), which were organized in the logical sequence and transferred into a personal computer at the end of each day. By video recording, the intention was to document the productive work time. As such, long rest breaks, meal pauses or other events that were characterized by long durations were not video recorded. In total, 71 media files were collected from the field, covering close to 24 h of video surveillance and they were used as inputs for the elemental time and motion study.

Data on the exposure to noise was collected at a sampling rate set at one second by implementing the full day measurement strategy, which was designed and deployed in compliance with the European legislation and relevant guidelines and standards [30,31]. The used noise-level datalogger meets the ANSI and IEC 61672 Class 2 standards [32] and its choice was based on the possibility to place it at a standardized distance from the ear of the operator, given the fact that noise is considerably attenuated even on short distances [33]. It was placed on a helmet following a procedure similar to that from [9], then the operator was instructed to keep the helmet on the head during the study. At the end of each day, the collected data were downloaded in a personal computer using the dedicated software.

As specific to the observed operations, the physical workload was not expected to be very high in terms of cardiovascular activity measured by the heart rate (HR, bpm); nevertheless, considering the high altitude at which operations were surveyed (more than 3000 a.s.l.), this parameter was monitored using the methods described in [9,33–35] and a sampling rate set at one second. Data were stored in the internal memory of the device, then the Polar FlowSync application (www.polar.fi, accessed on 15 December 2020) was used to download it as .CSV and .TCX files. Given the current problems related to the reliability of the minimum heart rate indicator [36], and to the robustness of estimating the maximum heart rate by the commonly used formula [37], no attempts were made to apply and follow any protocol to collect this kind of data in the field. Instead, the collected values were used for data processing and statistical analysis as they were obtained from the field observation.

The accelerometer was used only as a mean to collect additional data needed for a correct documentation of events, based on its property to respond to vibration. The field data collection protocol supposed a sampling rate of one second and an operation mode set as motion detection, using for this purpose a threshold set at 1 g. The device was attached to the backside of the operator's chair using adhesive tape, and the data collected by it were downloaded at the end of each day as .CSV files, by the means of the dedicated software.

2.3. Data Processing and Analysis

Time consumption data were extracted by a detailed analysis of the media files which was done at an accuracy of one second. A database was developed in Microsoft Excel® (Microsoft Excel 2013, Microsoft, Redmond, WA, USA), and each separable event was documented by the inclusion of the starting and ending time labels and of a short string code to indicate the work element to which it belonged. The processed trees were noted in their order of processing and each recovered log was included in the database, once a crosscutting occurred and a log was produced. While the time consumption analysis was done to the finest possible detail, a final decision was made based on data processing outcomes and the results of [27] to keep for further analysis only those data partitions covering entirely documented work cycles. Table 1 is showing the work and time consumption categories and elements, which were aligned to the general concepts used for time consumption analysis in forest operations [38].

Relevant variables characterizing the inputs, process and outputs were the number of processed trees as inputs (950 in the initial database), number of cuts performed as process variables (3099 in the initial database) and the number of recovered logs (3265 in the initial database) as outputs. The number of feeding and delimbing events (3259 in the initial database) were documented in detail, but their detailed statistical results were not used in this study.

The most relevant metrics which are commonly used to characterize the productive performance are the productivity and efficiency rates [38], which can be expressed by using both, the delay free and total workplace time, resulting in net and gross figures [39,40]. The main approach to characterize the productive performance was that of using the inputs (number of trees) as a parameter to compute productivity and efficiency rates. However, the number of recovered logs, as outputs, was used as a parameter to characterize the productive performance and capability of the machine by a graphical approach. Given the methods used to collect the time consumption data, the focus was on the net metrics, which were considered to be more robust.

Table 1. Description of work and time elements.

Work (Time) Element	Description	Procedures Used in Documentation
Recorded time	All the time covered by the media files	Documented in seconds, as the total amount
Undocumented time	Portion of the time covered by the media files which could not be documented due to camera movement or other events	Documented in seconds, as the total amount
Documented time	Portion of the media files for which codes could be attributed following the time and motion study procedures	Documented in seconds, as the total amount
Delays	Portion of the time in which no work was carried out due to events caused by personal or mechanical reasons. The category excludes the time spent in other events such as long rest breaks, meal breaks and other, for which the data was documented by the rest of the used devices	Documented in seconds, accounted as event-based and reported as the total amount
Moving to next pile	Non-cyclic time in which the machine was driven from a given pile to a location at which a new log pile was started. It started when the machine started to move and it ended when machine reached a new location	Documented in seconds, accounted as event-based and reported as the total amount
Piling tops & slash	Non-cyclic time in which the crane was used to pile the tops and slash resulting from tree processing. It occurred several times, but not on a cyclic basis according to the delay-free work cycle definition given in the following. It started when the crane started its movement to grip tops and slash and it ended when the crane reached to a location of starting a new work cycle	Documented in seconds, accounted as event-based and reported as the total amount
Piling logs	Non-cyclic time in which the crane was used to pile or to arrange some logs resulted from processing. It occurred occasionally. It started when the crane started its movement to grip logs and it ended when the crane reached to a location of starting a new work cycle	Documented in seconds, accounted as event-based and reported as the total amount
Arranging trees	Non-cyclic time in which the crane was used to arrange trees in the bunches to facilitate processing. It occurred occasionally. It started when the crane started its movement to grip trees and it ended when the crane reached to a location of starting a new work cycle	Documented in seconds, accounted as event-based and reported as the total amount
Delay-free work cycle time	Cyclic time consumption by considering a work cycle framed around a processed tree, and made of subsequent work cycles which were disregarded	Documented in seconds, accounted as event-based and reported by the means of the main descriptive statistics, including the total amount
Tree loading & gripping time	Elemental time in which the crane was used to load a given tree, and the rollers and knives were used to grip the tree. It started when the crane started its movement to grip a tree (or trees) and it ended when a tree carried by the crane was gripped in the processor	Documented in seconds, accounted as the sum of the time found for the described events and reported by the means of the main descriptive statistics, including the total amount
Delimbing, feeding & residue removing time	Elemental time in which the knives, rollers and the processor itself were used to feed a given tree, delimb it and to remove the processing residues and tops. It consisted of several instances of delimbing, feeding and, in many cases, of residue removing. It started when, following gripping, a tree started its movement powered by the rollers and it ended when the residues were removed by the rollers.	Documented in seconds, accounted as the sum of the time found for the described events and reported by the means of the main descriptive statistics, including the total amount
Crosscutting time	Elemental time in which the chainsaw of the processor was used to make cuts in a tree with the aim of detaching the logs. It consisted of one to several instances of crosscutting, depending on the number of recovered logs, and it accounted for all the time spent to make the crosscuts, including decision making, saw releasing and returning to its initial location. It started when the saw stared to exit from its storing device and it ended when it got back to its storing device.	Documented in seconds, accounted as the sum of the time found for the described events and reported by the means of the main descriptive statistics, including the total amount

Statistical analysis of the data on time consumption and productive performance followed the typical workflow described by several specialty studies [39,40]. In particular, the statistical design was oriented toward the development of descriptive statistics, and graphical comparison of the data. A normality check was undertaken by the means of the Shapiro-Wilk test (α = 0.05), then the main descriptive statistics were developed. While no exclusion of outliers was considered in this study because the data was carefully checked, for a better clarity of the presented information, some of the developed graphs were reported by the exclusion of statistically determined outliers. Statistical analysis, as well as all the graphical work given in this study were done by the means of Microsoft Excel software fitted with the Real Statistics ® add-in (Real Statistics, https://www.real-statistics.com/, accessed on 15 December 2020).

Data on the exposure to noise, heart rate and acceleration was complemented by the GPS data and it was processed by the use of a different approach, at a daily level. A data pairing procedure was used to synchronize the data strings characterizing the sound pressure level (dB(A)), acceleration (g), heart rate (bpm) and GPS speed (km/h), using for this purpose the time labels included in each dataset. Following pairing, an aggregated database was built to hold the parameters needed in the analysis, then a refining procedure was setup to remove that data which covered the events categorized as delays caused by the study (setup of the monitoring devices). The remaining data was concatenated and documented further to account for the observation day and to differentiate between processing and non-processing tasks; processing tasks were assumed to include all the productive tasks described in a work cycle, as well as those of moving or arranging trees, tops and logs. Task coding was undertaken by a visual analysis of the aggregated data patterns and it was based on informed grounds, by considering the magnitude of acceleration, sound pressure level and GPS speed. For instance, acceleration values of up to 1.1 g were used as a reference to infer that the data showing them belonged to non-processing category, a fact that was checked, in the time domain, against the pattern of the of the sound pressure level magnitude.

Cardio-vascular activity was characterized by the main descriptive statistics estimated from the field collected data, while the exposure to noise was evaluated by commonly used metrics [30,31,41]:

- A-weighted sound pressure level (*Laeq*), computed at task group (processing and non-processing tasks), daily and overall resolution;
- A-weighted sound pressure level (*Laeq*, *T*), weighted by the number of days of observation;
- Exposure to noise normalized for a nominal 8-h working day ($L_{EX,\,8h}$).

Data reporting by graphs and tables was supported by the software tools used in the time consumption analysis and, when possible, the data were reported at the finest level of detail (task group).

3. Results

3.1. Time Consumption and Estimates of Productive Performance

The detailed analysis of the media files has covered 69,914 s (ca. 19.4 h) and a number of 950 processed trees from which were recovered 3265 logs. Following the removal of data coming from those media parts that did not provide enough information to analyze full work cycles, the time consumption kept into analysis was of 64,281 s (ca. 17.9 h) and it accounted for 901 processed trees from which a number of 3113 logs were produced (Table 2). Approximately 17% of that time information was lost due to the impossibility to document it.

In the documented time (ca. 14.8 h), delays accounted for close to 6% (Table 2). Work tasks that were considered to be outside a typical work cycle were those of moving between wood piles, piling tops, processing slash and logs, and arranging the trees in the bunches before loading them into the processor. These accounted for close to 2.6 h (ca. 18% of the documented time) and were included in the computation of gross and net productive performance metrics. The delay-free work time accounted for close to 11.3 h and dominant in its structure were the loading and gripping time (40.3%) as well as delimbing, feeding and residue removing time (49%). Crosscutting time accounted for 10.7%. On average, a delay-free work cycle accounted for close to 45 s (Table 2), but it varied quite widely (Table 2, Figure 2), up to 5 min, mainly due to the processing of some trees which were either curved, larger (i.e., rightmost boxplots from Figure 2 showing the data of those work cycles following which 5 to 7 logs were recovered) or they had a strongly-developed limb; for instance, there were 15 trees that required more than one minute for delimbing.

Table 2. Descriptive statistics of production.

Variable	Measurement Unit	Descriptive Statistics *				
		N	Minimum Value	Maximum Value	Mean (Median) Value	Sum (Share)
Number of processed trees		901	-	-	-	-
Number of recovered logs		3113	1	7	3.46 (3.00)	-
Time consumption						
Recorded time		-	-	-	-	64,281 (100)
Undocumented time	s	-	-	-	-	11,126 (17.3) [a]
Documented time	s					53,155 (82.7) [a]
Delays	s	144	-	-	-	3071 (5.8) [b]
Moving to next pile	s	6	-	-	-	445 (0.8) [b]
Piling tops & slash	s	349	-	-	-	4760 (9.0) [b]
Piling logs	s	205	-	-	-	2318 (4.4) [b]
Arranging trees	s	48	-	-	-	1923 (3.6) [b]
Delay-free work cycle time	s	901	3	300	45.10 (43.00)	40,638 (76.4) [b]
Tree loading & gripping time	s	899	1	69	18.20 (17.00)	16,358 (40.3) [c]
Delimbing, feeding & residue removing time	s	898	4	272	22.19 (19.00)	19,924 (49.0) [c]
Crosscutting time	s	893	1	13	4.88 (5.00)	4356 (10.7) [c]
Gross Productivity Rate	trees $\times$ h^{-1}	-	-	-	61.02 [d]	-
Net Productivity Rate	trees $\times$ h^{-1}	-	-	-	64.76 [e]	-
Gross Efficiency Rate	h $\times$ tree^{-1}	-	-	-	0.016 [f]	-
Net Efficiency Rate	h $\times$ tree^{-1}	-	-	-	0.015 [g]	-

Note: * all the variables failed the normality tests; [a] share in the recorded time, [b] share in the documented time, [c] share in the delay-free work cycle time, [d] computed as the ratio of the number of processed trees to the documented time, [e] computed as the ratio of the number of processed trees to the documented time, excluding delays, [f] computed as the ratio of the documented time to the number of processed trees, [g] computed as the ratio of the documented time, excluding delays, to the number of processed trees.

Crosscutting time averaged close to 1.4 s per cut (data not shown herein). However, the average cumulated crosscutting time depended largely (R^2 = 0.92) on the number of cuts done per processed tree, by a factor (regression slope) of ca. 1.5. A breakdown showing the variation and central tendency of the cumulated accumulated time as a function of the number of cuts is given in Figure 3.

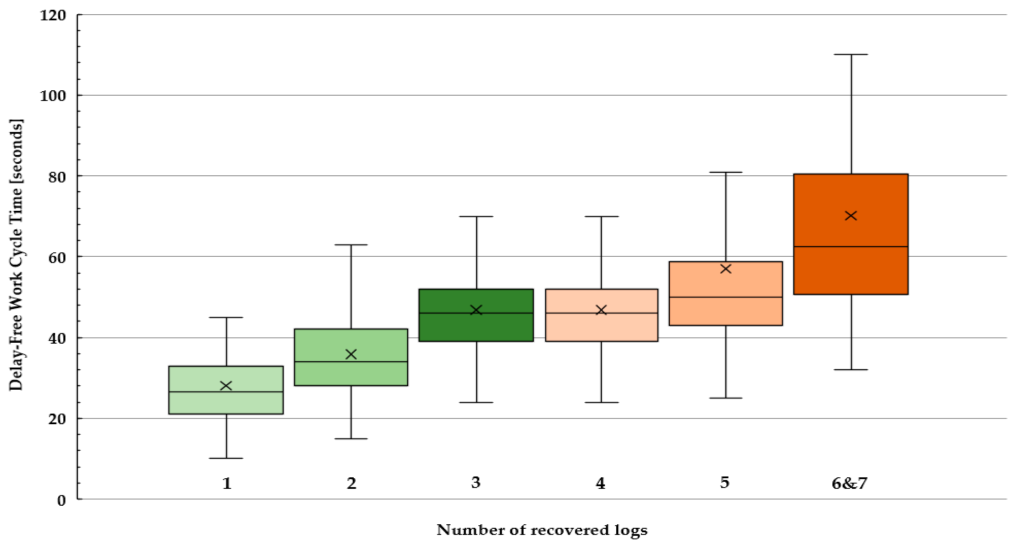

Figure 2. Variation of delay-free work cycle time as a function of the number of recovered logs. Legend: × stands for the mean value. Note: outliers not included in the figure.

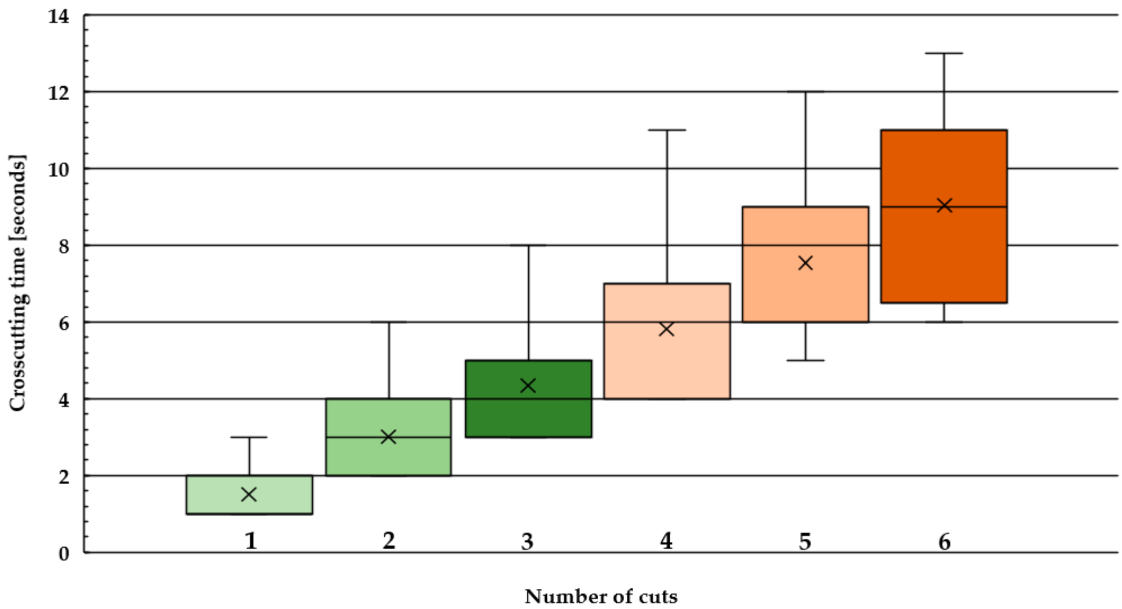

Figure 3. Variation of cumulated crosscutting time as a function of the number of crosscuts. Legend: × stands for the mean value. Note: outliers not included in the figure.

The delays affected the productivity and efficiency. For instance, the net productivity rate, based on the inputs (trees), was found to be of close to 65 trees processed per hour and it decreased to ca. 61 trees per hour when the delays were included in its estimation. Accordingly, the estimated gross and net figures of efficiency were of 0.016 and 0.015 h per tree, respectively (Table 2).

When accounting for the number of logs produced (Figure 4), the net productivity rates varied largely as an effect of the time consumption categories included in their estimation. As such, the net productivity rate estimated by considering the documented time and by excluding the identified delays, accounted for ca. 224 logs per hour. For comparison purposes, as well as for the indication of potential limits of capability, Figure 4 are showing also the net productivity rate based on the delay-free work cycle time (ca. 275 logs per hour) plotted against its variation as a function of the number of recovered logs. As shown, up to a number of 5 logs the productivity rate increased steadily; beyond this point, however, its curve based on the average values started to flatten or even decrease. It is worth mentioning here that the data shown in Figure 4 is based on observations that covered 49, 165, 243, 245, 156, 38 and 2 instances in which were recovered 1, 2, 3, 4, 5, 6 and 7 logs, respectively, a fact that applies also to the data shown in Figure 2.

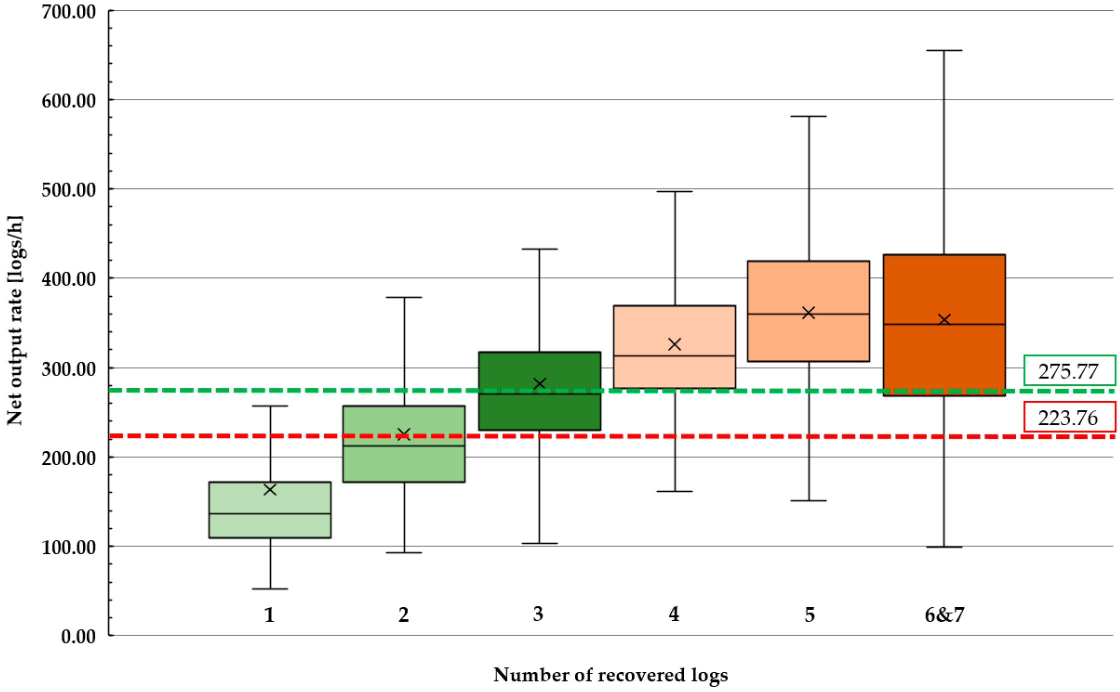

Figure 4. Variation of output rate as a function of the number of produced logs. × stands for the mean value. Note: outliers not included in the figure. Legend: green dashed line—net output rate based on the delay-free work cycle time, red dashed line—net output rate based on the documented time, excluding delays.

3.2. Cardiovascular Workload and Exposure to Noise

Following the removal of data covering those events characterized as delays caused by the study, the final dataset accounted for 100,580 s (ca. 27.9 h), out of which, 60,312 s (ca. 16.8 h) were found to belong to the processing work tasks. The figure was very close to that found for the data used in the analysis of time consumption and productive performance metrics, which was of 64,281 s, of which 3071 were identified as different kinds of delays and 11,126 s were undocumented (Table 1). Accordingly, by removing the delays, one may obtain 61,210 s that were potentially used to process trees. Figure 5 shows a breakdown of the data characterizing the acceleration, heart rate and sound pressure level on days of observation and event categories. Close to 40% of the data were found to belong to non-processing events which may characterize very well delays, lunch breaks and other movements, indicating a machine utilization rate estimated at ca. 60%. However, the observed time and utilization rates varied across the operational days taken into the study. For the first parameter, values of 20,520 (ca. 5.7 h), 31,688 (ca. 8.8 h), 29,813 (ca. 8.3 h) and 18,559 s (ca. 5.2 h) were found in the first, second, third and fourth days, respectively. For the same days, the utilization rate of the machine was estimated at ca. 75%, 62%, 59% and 41%, respectively.

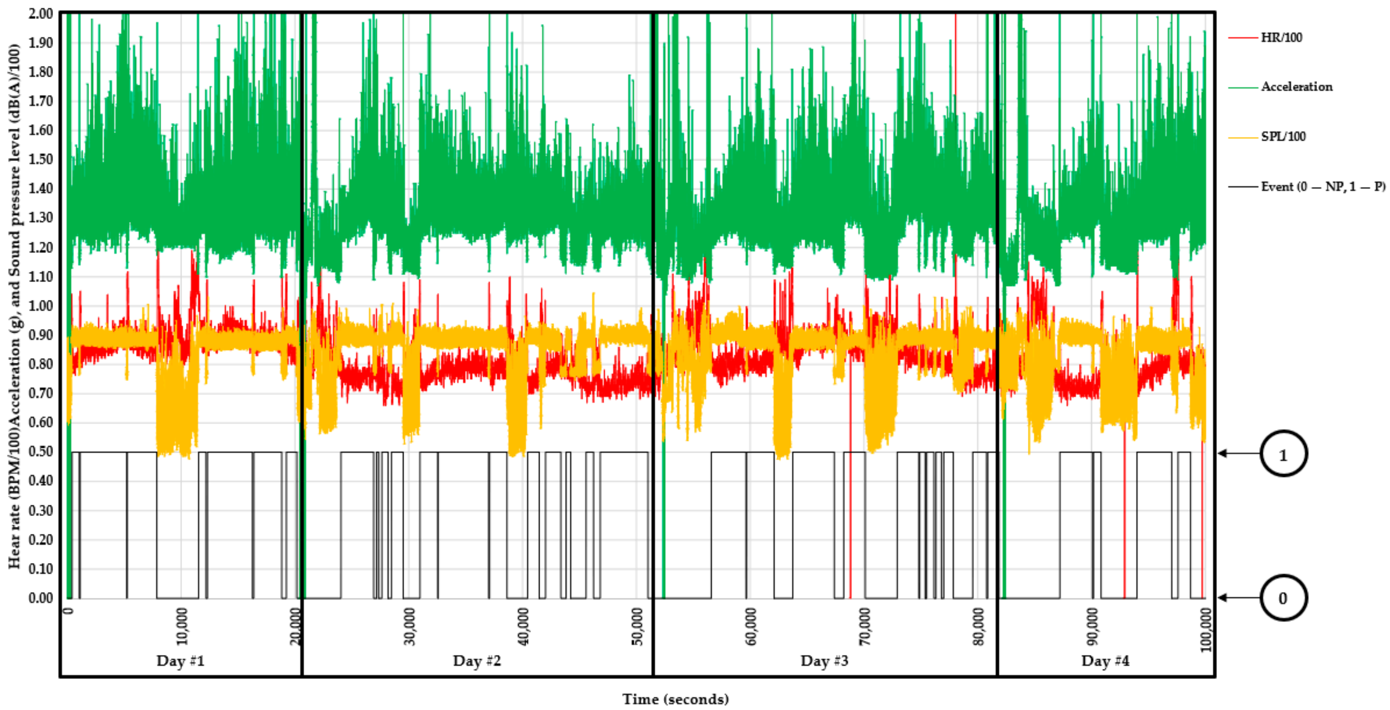

Figure 5. Variation of the heart rate, acceleration and sound pressure level in the time domain and on events. Legend: *HR/100*—heart rate (beats per minute) downscaled by a factor of 100, *SPL/100*—sound pressure level (dB(A)) downscaled by a factor of 100, *NP*—non-processing events (time), *P*—processing events (time).

A description of the heart rate data dynamics is given in Figure 6, indicating the general trend of having a much higher heart rate response during non-processing events. This fact was supported by two parameters, namely the magnitude of the parameter and its amplitude. During processing, heart rate response was considerably lower in magnitude when compared against the non-processing events, and it was also characterized by a lower variation in the amplitude domain. In numbers, the whole dataset was characterized by a minimum, maximum and an average value of 65, 201 and 83 beats per minute, indicating, overall, rather a low-demanding cardio-vascular activity. However, for the same basic statistics, processing events, which accounted for ca. 60% of the time, were characterized by figures of 66, 119 and 81 beats per minute, which were lower compared to those of non-processing events (65, 201 and 86 beats per minute). One has to mention that non-processing events included the operator walking to a place of eating and back. Another thing which can be observed is that of an evident variation of this parameter at daily and inter-daily resolution.

A similar data pattern was found for the sound pressure level, whose variation in the time and amplitude domains is shown in Figure 7. Processing events were found to generate values in between ca. 85 and 97 dB(A), being generally much higher compared to non-processing events. Similar to the heart rate, the variation in amplitude was much higher during non-processing events. It is worth mentioning here that some events such as operating a chainsaw in the processing area or the interference of other machines in the working area could not be separated from the used data and, at least the first one may have affected some data. However, these events occurred seldom, a fact that was learned from the analysis of the media files.

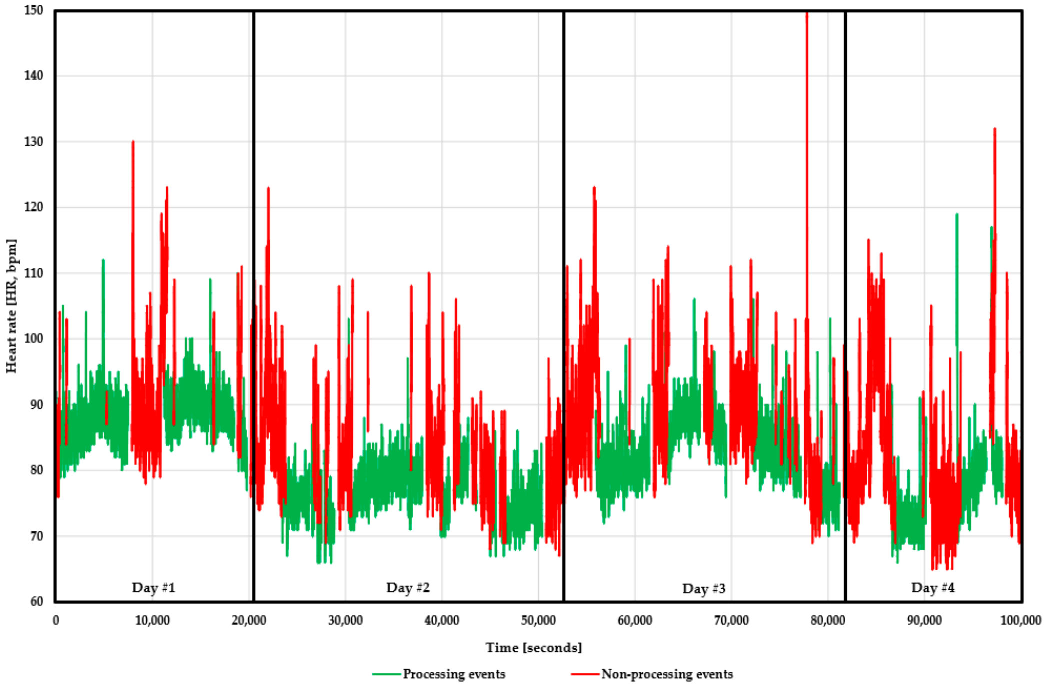

Figure 6. Variation of the heart rate (*HR*, bpm) in the time domain for the four observed days. Legend: red—non-processing events (time), green—processing events (time).

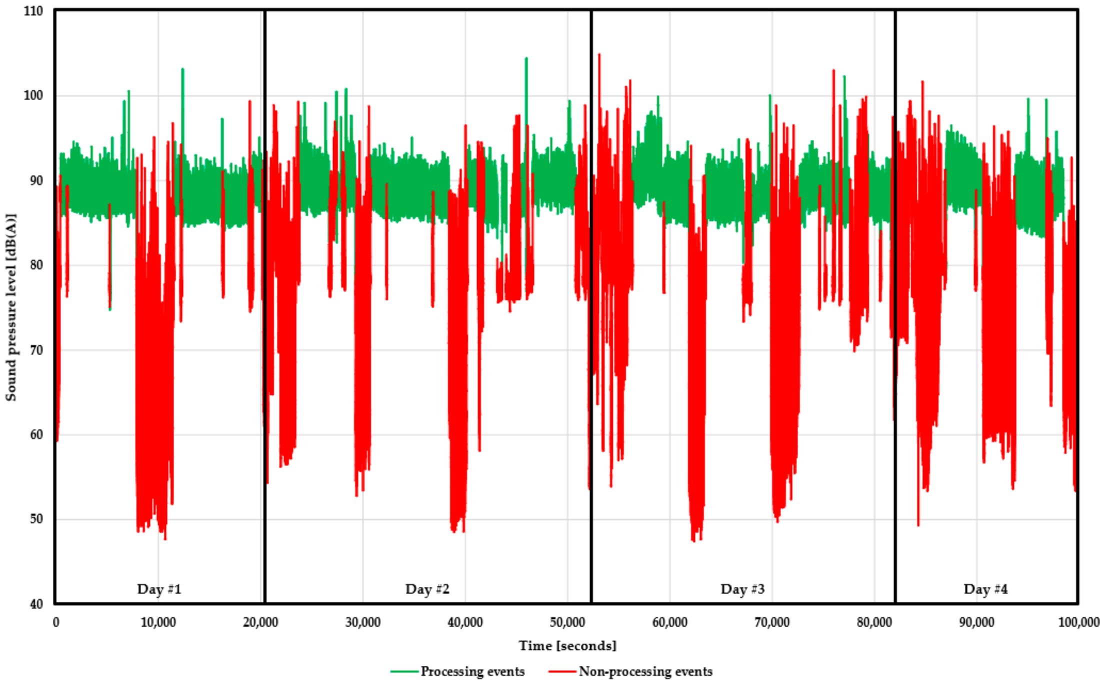

Figure 7. Variation of the sound pressure level (*SPL*, dB(A)) in the time domain for the four observed days. Legend: red—non-processing events (time), green—processing events (time).

Values of the parameters commonly used in the assessment of exposure to noise are given at daily and overall resolutions in Table 3. The A-weighted sound pressure level (*Laeq*) computed at daily resolution indicates values of exposure exceeding 85 dB(A) irrespective of the day of observation. However, there were important differences between the event classes as regards this parameter. Systematically, non-processing events produced sound pressure levels which were lower by at least 5 dB(A). For the four days taken into study, the A-weighted sound pressure level (*Laeq*) averaged 87.36 dB(A). This was generally over the exposure limit set at 87 dB(A) and, particularly, the first three days of observation exceeded this threshold. Irrespective of the analyzed class of events or day of observation, the values found for this parameter were close or exceeded the minimum action level set at 80 dB(A) by [30]. When accounting for the number of days taken into the study (*Laeq*, *T*), the exposure to noise was found to be of 87.26 dB(A). For the last parameter ($L_{EX,\ 8h}$), which normalizes the data on the exposure to noise for a nominal day (8 h in this study), the value was 92.79 dB(A) and it was mainly the result of the machine utilization rate in the processing events, which was close to 60%, as well as of the daily duration of the operations which was, on average, 7 h per day.

Table 3. Statistics of the exposure to noise.

Parameters	Metrics of the Exposure to Noise			
	Time (Seconds)	***Laeq* [dB(A)]**	***Laeq, T* [dB(A)]**	**$L_{EX,\ 8h}$ [dB(A)]**
Day # 1	20,520	87.21	-	-
Non-processing events	*5193*	*78.50*	-	-
Processing events	*15,327*	*88.33*	-	-
Day # 2	31,688	87.82	-	-
Non-processing events	*11,919*	*83.48*	-	-
Processing events	*19,769*	*89.22*	-	-
Day # 3	29,813	87.48	-	-
Non-processing events	*12,279*	*83.25*	-	-
Processing events	*17,534*	*89.06*	-	-
Day # 4	18,559	86.38	-	-
Non-processing events	*10,877*	*82.36*	-	-
Processing events	*7682*	*89.07*	-	-
Overall	100,580	87.36	87.26	92.79

4. Discussion

Unfortunately, there were no available data to effectively compare our results on the productive performance for the same type of equipment, and the measurement of production inputs and outputs in cubic meters was not possible in this study.

The impossibility to compare the results was due to the fact that most of the literature on double-grip machines was found to be published in the 90′s and it was not available in English for a detailed comparison. In addition, it refers to double-grip harvesters used for tree felling and processing operations deployed in forest stands [23], making it difficult to compare the results due to different inputs and operational environment of this study; however, the study of [23] compared the productivity of single- and double-grip harvesters, concluding that there were rather minor differences in terms of productive performance in tree felling and processing operations deployed in shelterwood silvicultural systems.

In terms of production measurements, this study has used a counting procedure as a mean to treat the production input and output variables, which fits well when one can assume a low variability in the dimensional features, such as those of tree and log size [40]. However, if one assumes for the studied conditions an average tree volume of 0.07 m^3 [42], which could be reasonably close to the real figure, and by considering all the productive time, including that of moving, piling and arranging trees, then processing one tree would take close to one minute and the total production measured in this study will be close to a figure of 63 m^3. In such conditions, ca. 60 trees would have been processed per hour, resulting in a net productivity rate of ca. 4.2 m^3 per hour. Then, the gross figures could be given by considering the machine utilization rate which was estimated by this study at ca. 60%. Accordingly, the gross productivity rate would be of ca. 2.5 m^3 per hour. These results may be characterized by global net and gross efficiencies of 0.24 and 0.40 h per cubic meter.

Compared to single-grip processors equipped with two chainsaws, the results of this study seem to follow the general piece-volume law, whose grounds are explained in [1].

For instance, Borz et al. [13] have found a net productivity rate of ca. 13 m^3 per hour for a single-grip processor operating at landing to process spruce trees from selective thinning operations (average tree volume of 0.21 m^3 per tree), which in terms of efficiency means an amount of 0.08 h needed to process one m^3. Therefore, in a comparison approach, tripling the average tree size will triple the productivity and decrease the efficiency by a factor of 3. However, it has been shown that a similar operational behavior works this way up to a capability declining point induced by the tree size [43]. This could be the case of our study if one checks the data given in Figure 4, which indicates the productivity in terms of logs per hour as a function of the number of recovered logs. As indicated there, the productivity trend was to increase up to a number of 5 recovered logs after which the mean value of productivity started to flatten or even to decrease. Since the crosscutting time had a minor effect (Figure 3) by its contribution to the time consumption, it is likely for this behavior of productivity data to come from the variation of tree delimbing time.

Performance of tree processing depends largely on the number recovered logs, with the difference that the motor-manual approach exhibits fewer capabilities in terms of tree hoisting functions and operational speed. This often results in considerably higher productive performances when using fully mechanized equipment, even though the time consumption variation will still increase as the number of recovered logs will increase [6]. The effect that a different operational environment (i.e., processing in the forests or at the landing) would have on the productive performance is difficult to estimate at this point due to the missing comparative data. Nevertheless, for this case study, a comparative evaluation with the motor-manual approach would be in question to confirm the hypothesized improvements. While there were no data available for such an attempt, for similar operational conditions in terms of tree size and workplace conditions, one could expect a productivity rate in the range of 1 to 1.4 m^3 per hour just to delimb the trees [44]. Accordingly, these productivity rates may translate very well in efficiency rates of 0.7 to 1 h per m^3, indicating a performance of the studied equipment which may be 3 to 4 times higher compared to motor-manual operations.

The aforementioned lead, naturally, to some comparison of the ergonomics parameters. We did not expect to find high figures of cardio-vascular activity due to the typical way in which the operation was carried out, as a cabin environment can provide improved working conditions. From this point of view, our findings indicate rather a normal and sustainable way of doing the work, with a cardiovascular activity averaging 83 bpm during the productive time, which was lower compared to that found for nonproductive time (86 bpm). Both, in terms of average figures, and magnitude variability, our results are consistent with those reported by [45] for the Japanese operational conditions.

Compared to the motor-manual alternative [9,46] the mechanized tree processing by double-grip machines seems to be far less demanding from the point of view of cardiovascular activity. This may be explained by the comfort provided by the machine's cab and by the sitting posture of the operator during the productive time, which could be double-checked by the findings on similar operations surveyed by simulation [20]. Motor-manual and mechanized tree processing operations share a common biomechanical feature which is the use of manual labour either to handle the chainsaw or the controls of a given machine. It is known that the hand-work contributes to a greater extent to the heart rate increment compared to the use of other parts of the human body [47]; however, there is a significant difference in terms of muscular work severity between the motor-manual and fully mechanized options, with the first one being more demanding due to the need to carry rather heavy equipment. For comparison, similar operations undertaken by chainsaws have returned figures of 114–123 bpm [9], while the light work may be characterized by heart rates of up to 90 bpm [47].

In terms of exposure to noise, both options (motor-manual, fully mechanized) may lead to exposures that require ergonomics intervention, with the main differences resting in the distance of the operator's ear from the noise source and in the pressure of noise generated by the source. The motor-manual alternative may expose the workers to considerably higher noise doses than the mechanized one, due to a higher pressure of sound during operation of the chainsaw [33] and due to a much smaller distance between the ear and the noise source [9]. In particular, the study of [9] has found A-weighted noise exposure levels of 102–104 dB(A) for tasks which are similar to those which would suppose motor-manual tree processing at landing, meaning a difference of more than 10 dB(A) if compared to the results of this study (ca. 88–89 dB(A)).

Therefore, two things need to be addressed here: awareness of the worker and wearing protective equipment. Even if not explicitly given in this study, our observations indicated that the cab door was open for more than 50% of the observed time. While it is to be checked if a closed door could have provided significant protection against the noise, still, this measure could be better than nothing in order to attenuate the noise produced by the machine in operation. Mechanized tree felling and processing may generate A-weighted sound pressure levels of up to 95 dB(A) during the operations [22], therefore, depending on the operational and environmental conditions, supplementary measures, such as wearing protective equipment, could be required. Acknowledging the potential discomfort generated by wearing a helmet equipped with features for protection against noise, and by taking into consideration that simple helmets could be sufficient as a head protection measure due to the operation from inside a cab, a solution that could be suitable for the studied operations would be that of using ear plugs which are supposed to provide attenuation of at least 15 dB(A) [33]. For that reason, we have simulated the results on exposure to noise by a reduction of 10 dB(A) applied to the whole data range (detailed results not included herein). Under this scenario, the global figure of *Laeq* metric was of ca. 77 dB(A) and that of $L_{EX,8h}$ metric was of ca. 83 dB(A), showing, therefore, a significant improvement that could be gained by wearing personal protective equipment. However, these new figures apply for a machine utilization rate of ca. 60%, and it is to be checked to what extent an increment of productive time would affect them, by considering also the differences in the regulations and thresholds specific to different parts of the world [30,33]. For instance, the European directive [30], which was used herein, describes minimum and maximum exposure limits that require intervention ($LE_{X,8h}$ of 80 and 85 dB(A), respectively), for which the protective equipment is not considered, as well as an exposure threshold of $L_{EX,8h}$ = 87 dB(A), for which the measurement should be taken by considering the wearing of protective equipment.

5. Conclusions

Pending a careful analysis and action taking to limit the occupational exposure to noise, the rest of the results found by this study indicate that the transition from motor-manual to fully mechanized tree processing operations of small-sized coniferous wood is a sustainable approach to be taken. It is still to be checked to what extent the increment of utilization rate could change the figures on the exposure to noise. However, ear protection and operator awareness are the main measures that could ensure the sustainability of operations even if the machine would be better utilized. Environmental impact and operational costs were not evaluated in this study. Therefore, further research should be developed in this direction given the extension potential of such operations in different regions the world. Besides operational costing, such studies should address also the variability of production inputs in terms of tree size to be able to extend the results of this study.

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