Delimbing and Cross-cutting of Coniferous Trees–Time Consumption, Work Productivity and Performance

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Abstract: This research established the time consumption, work time structure, and productivity for primary processing in felling areas of coniferous trees felled with a chainsaw. Delimbing and partial cross-cutting were taken into consideration. The research was conducted in a mixed spruce and fir tree stand situated in the Carpathian Mountains. The team of workers consisted of a chainsaw operator and assistant with over 10 years of experience. The results indicated a total time of 536.32 $s \cdot m^{-3}$ (1145.26 $s \cdot tree^{-1}$), work performance (including delays) of 6.716 $m^3 \cdot h^{-1}$ (3.14 $tree \cdot h^{-1}$), and work productivity (without delays) of 35.459 $m^3 \cdot h^{-1}$ (16.58 $tree \cdot h^{-1}$). The chainsaw productivity during tree cross-cutting was 82.29 $cm^2 \cdot s^{-1}$. Delimbing accounted for 96.18% of the real work time, while cross-cutting accounted for 3.82%. The time consumption for delimbing and cross-cutting, as well as the work productivity and performance in the primary processing of coniferous trees in the felling area, were influenced by the breast height diameter, stem length, and tree volume, while the chainsaw productivity was influenced by the diameter of the cross-cut sections. The relationships between the aforementioned dependent and independent variables were determined by simple and linear multiple regression equations.

1. Introduction

Wood harvesting management has multiple objectives that must ensure good wood valuing under profitable economic conditions, while trying to meet the requirements imposed by the sustainable management of forest resources and management targets established for each tree stand. Under these circumstances, the primary processing of felled trees plays an important role because this process ensures better conditions for superior wood valuing [1–3], economically and ecologically efficient wood harvesting [4,5], and full valuing of the marketable volume of marked trees. Primary processing is a critical step in the processing of standing timber into end products and plays a fundamental role in determining the profitability of a forest company [6].

The primary processing of felled trees is a technological process that involves the transformation of a felled tree into different raw wood assortments by delimbing, cross-cutting, debarking, splitting, or chipping. The primary processing operations needed are established in accordance with the characteristics (dimensions, quality, etc.) of the wood assortments to be made. The primary processing of felled trees is defined by the venue (in the felling area and landing), processing level (partial or full), and objectives (wood quality valuing or meeting the requirements imposed by the beneficiaries of the raw wood assortments).

Chainsaws are still important in tree felling [7] and processing in mountainous areas, where the harvester and the forwarder (CTL method) cannot be used. Moskalik et al. [8] have presented the share

of chainsaw use in tree harvesting in Eastern European Countries. Thus, the chainsaw is used in tree felling and processing: 59% in Belarus, nearly 100% in Bulgaria, 71% in Czech Republic, 5% in Estonia, 30% in Latvia, 80% in Poland, 98% in Romania, 95% Slovakia, and nearly 100% in Ukraine. Chainsaws are still used even in Nordic countries, where they are preferred by small-scale operators, especially when dealing with biomass production. They are also used in forest owner operations and birch veneer log harvesting [9]. Because the cut-to-length (CTL) method is potentially damaging to logs and reduces their value, it should not be used to harvest large diameter, high-quality trees. Also, CTL systems should not be used on slopes in excess of 30%. Manual felling and processing are preferred in these situations [10]. The most sensitive and demanding sites are felled using a chainsaw [11]. Logging equipment such as feller-bunchers, harvesters, and forwarders are expensive to own and operate [12]. Wang et al. [13] reported that many loggers were hesitant to commit to the high investment costs of a harvesting system due to lack of confidence that the system would produce enough volume to be profitable.

The system used most frequently in wood harvesting, in the Romanian Carpathians, in the case of thinning or silvicultural treatments, is the cutting of trees with a chainsaw, logging by skidders or animals (horses and oxen), or skyline yarding. The CTL method is rather scarcely applied, on the one hand, because of the high investment cost, and, on the other hand, because of the Romanian relief (approximately 60% of forests are situated in mountainous areas) and of the small prevalence of coniferous trees (approximately 30%) [14,15] estimated that the CTL method can only be used for 10.5% of the stand surface, the most important limiting factors being tree diameter at stump level, ground slope, high investment cost, and a small surface (maximum three hectares) of the felling area in coniferous species in clear cutting (spruce and pine) [16]. About 16 to 18 million m^3 of wood is harvested annually from Romanian forests, out of which 30 to 40% is coniferous wood [17]. The wood is harvested by 5185 accredited logging companies from forests owned by the state—about 50.2%—and from private forests—about 48.8% [17]. Individual owners may harvest at most 20 m$^3 \cdot$year^{-1} of the total forest that they own. Private properties represent 48.8% of the national forests surface [18]. In 2011, there were approximately 830,000 private properties, out of which 828,000 had a surface smaller than 10 hectares and 2200 had a surface above 10 hectares. The number of private properties is on the rise because the retrocession process is not over yet and there are still numerous lawsuits taking place. It may be estimated though, that when all retrocession is over, state owned forests will represent about 40% of the national forests surface [19].

If the work conditions in Romania are taken into consideration, it can be said that the primary processing of felled trees takes place partially in the felling area with a chainsaw and fully in the landing. To do this, the full delimbing and partial cross-cutting operations are performed in the felling area after the felling. The two operations have distinct characteristics, among which the most important are delimbing, which is a highly risky and time-consuming operation [4,20], and cross-cutting, which is considered to be the most important work task [21,22] if wood valuing and the length of the resulting pieces are taken into consideration.

The partial primary processing of felled trees in the felling area aims to create the best conditions for extraction [23] so that the logs respond to the movement possibilities of the equipment. It also aims to ensure good delivery conditions of raw wood assortments for specific lengths and to meet ecological requirements [1,4,6].

Tree delimbing and cross-cutting as stages of the primary processing of felled trees in the felling area have not been extensively studied. In some studies, these operations were considered stages of the felling operation. For example, [24,25] included delimbing in the felling operation. Tree delimbing and cross-cutting in the felling area take more time than felling itself. In the felling area analysed in this study, 1 m^3 of wood was felled in 316.5 s (the felling operation was studied using a similar methodology under similar working conditions and the results were presented in a previous article) [26], while the delimbing and cross-cutting of 1 m^3 of wood took 536.32 s. [25] showed that delimbing and cross-cutting accounted for 43.98% of the felling operation (2.01 min·tree^{-1} and 4.57 min·tree^{-1},

respectively). [27] showed that felling took approximately 20% of the productive work time, and delimbing took 46% of the productive work time. Delimbing and cross-cutting are performed by using specific methods and work techniques, during which the chainsaw operator and assistant are exposed to other risks [28]. All of these factors justify the need to study delimbing and cross-cutting in a felling area as operations distinct from felling.

The time consumption and structure during delimbing and cross-cutting operations are influenced by quantifiable factors, including the work conditions (characteristics of the land, tree stand, marked trees, season, etc.), technical characteristics of the work equipment, qualification level and experience of the chainsaw operator, and work techniques [29,30]. There are other influencing factors whose variability cannot be quantified, such as the motivation and salary of the chainsaw operator and the level of work planning and organization [31]. The simultaneous action of these factors, as well as the different influences that each factor has, can lead to noticeable productivity differences under apparently similar working conditions from one work place to another. That is why research concerning time consumption and structure of the primary processing of felled trees must only take into account the relevant influencing factors [32]. Research concerning time consumption during the primary processing of felled trees has focused on establishing specific correlations between the size and structure of this parameter and a wide range of influencing factors, such as the breast height diameter (dbh), treatment applied [24], average tree volume (V), length (l) of the pieces resulting from cross-cutting [33,34], sum of cross-cut diameters in a tree, technical characteristics of the equipment used [35], and experience of the chainsaw operator [20].

Work productivity, which is defined as the ratio of output to input [36], is influenced by the same factors that influence the time consumption [3,24,29]. The efficiency of primary processing of felled trees in the felling area can be increased by understanding the structure and time consumption of each operation and stage, as well as the corresponding level of work productivity. The work time structure and productivity are basic elements for programming and planning activities, choosing the correctly sized work team, cost estimation, fuel and lubricant consumption, and emphasizing the need for diversifying and perfecting work techniques and equipment [37–39]. An analysis of time consumption creates the premise for the identification of the main factors which determine work time variations and, in this way, the identification of possibilities for the improvement of work techniques and the characteristics of the chainsaw. Sound knowledge of the factors which influence work time allows for better planning of harvesting operations so that deadlines can be met and damage to forest ecosystems be minimized. The models to be developed should be appropriate for giving accurate productivity estimates in coniferous harvestable stands from mountainous areas, as well as for cost calculations and different kinds of modelling and simulation purposes [26].

This research aimed to determine the work time, productivity level, and structure of the primary processing of felled coniferous trees, specifically during full delimbing and partial cross-cutting with a chainsaw in felling areas in a mountainous area in Romania.

2. Materials and Methods

2.1. Research Venue

This research was conducted in a felling area on the southern face of the Southern Carpathians in the Iezer-Păpuşa Mountains in Romania with the latitude between 45°25′ and 45°30′ N and the longitude between 24°50′ and 24°54′ E. The altitude ranged from 900 m to 1300 m with an average slope of 33° (65%). The tree stand contained a mix of spruce (*Picea abies* L. Karst.) and fir (*Abies alba* Mill.) trees, where a group shelterwood system had been applied. The characteristics of the marked trees are presented in Table 1.

Table 1. Characteristics of marked trees.

Marked Tree Characteristics	
Total volume (m^3)	2376
No. of trees	1063
Average tree volume (m$^3 \cdot$tree^{-1})	2.24
Dbh (cm)	56
Average height (m)	29
Pruning (%)	60
Distance between marked trees (m)	10.8

2.2. Field Data Collection and Equipment

The cut-to-multiple-length method was applied in the felling area that was analysed. This method involves the primary processing of felled trees in the felling area by full delimbing and partial cross-cutting. By using this method, the resulting logs may include the length of one wood assortment or lengths of two or three assortments. The choice for the cross-cutting spot is extremely important to provide the best conditions for wood valuing. Thus, for cross-cutting in the felling area, the requirements for cross-cutting to value and demand were taken into consideration [40].

In this research, the delimbing and cross-cutting of trees in the felling area took place simultaneously. A single team of chainsaw operators that consisted of one chainsaw operator and an assistant was used for all of the measurements. The chainsaw operator was in charge of delimbing and cross-cutting. During delimbing, the chainsaw operator cuts the branches and top of the trees and maintains the chainsaw, and the assistant is in charge of moving branches away from the stem and rolling the wood to cut the branches from under the stem. During cross-cutting, the chainsaw operator performs the cutting and maintains the chainsaw, and the assistant measures and marks specific spots for cross-cutting and assures the stability of the tree and resulting wood pieces on steep slopes. Also, the assistant is responsible for wedging in the case of tension wood and helps to remove the bar of a trapped chainsaw. The chainsaw operator used the same chainsaw (Husqvarna 365) in all of the operations performed in the felling area. The main technical characteristics of this chainsaw were a cylinder displacement of 65.1 cm^3, power output of 3.4 kW, bar length of 45 cm, and weight (without bar and chain) of 6 kg. The level of qualification and experience for the work team (over 10 years) corresponded to the operations performed. The skill of the chainsaw operators, which is defined by the number of delimbed and cross-cut trees, exceeded the recommended value of 8000 [36]. The equipment used had approximately 2000 h of use, which represents the average lifecycle of a piece of equipment from this category under normal production conditions [41,42].

This research involved the analysis of time consumption and structure at the work shift, operation, and stage levels. The classification suggested by [43] was used to analyze the total work time structure. Thus, the following elements were measured: (i) time consumption in the work place, time for actual work activities, and time for unproductive activities; and (ii) time consumption for activities conducted outside of the work place.

The unitary action from an operation, which is strictly necessary from a technological point of view and mandatory for the normal development of the production process, was considered a work stage. A series of other activities that are not absolutely necessary from a technological point of view were added to these. These activities provided the working conditions imposed by labour standards for occupational safety and health, the specific activities in forestry, and ergonomic and physiological requirements.

The detailed work time structure that was divided into operations, stages, and associated activities is presented in Table 2.

Table 2. Work time structure in delimbing and cross-cutting operations.

Work Time Structure					Operation	Stage	Activity
TT	WP		NW		Delimbing Cross-cutting	-	Moving to and from the work place at the beginning and end of the schedule
			NT		Delimbing Cross-cutting	-	Meal, rest, necessities, and organisation
		WT	PW	MW	Delimbing Cross-cutting	tcv s	Delimbing and top removal; Partial cross-cutting in the felling area
				CW	Delimbing Cross-cutting	tcv s	Branch and top removal; Measuring length of the wood pieces and choosing the cross-cutting spot
			SW	PT	Delimbing Cross-cutting	tcv s	Tree stability analysis; Wood piece analysis and establishment of the length of the resulting wood pieces
				ST MT	Delimbing Cross-cutting	-	Saw chain sharpening and chain tension; Saw chain replacement and guide bar turning; Cleaning the air filter
				RF	Delimbing Cross-cutting	-	Chainsaw fuelling with mixed fuel and oil for chain lubrication
				AW	Delimbing Cross-cutting	tcv s	Providing stem stability; Wedging in tension wood cross-cutting

TT—total time; NW—non-workplace time; WP—workplace time; NT—non-work time; WT—work time; PW—productive work time; SW—supportive work time; MW—main work time; CW—complementary work time; PT—preparatory time; ST—service time; AW—ancillary work time; MT—maintenance time; RF—refuel time; tcv—delimbing; s—cross-cutting in the felling area; adapted from [43].

By using a single research and work team, the variation of the work time structure depending on the felled wood dendrometric parameters was determined more precisely. The following aspects were considered permanent characteristics or constants: the physical and geographical features, silvo-technical conditions, team of chainsaw operators, work equipment, and research team.

Considering the importance of clearly defining each stage, including the beginning and end [37], the technological stages of the primary processing of felled trees were divided into the following categories: (1) delimbing (tcv)—cutting and removing the branches and top: begins when the feller starts delimbing the tree and ends when all of the branches are cut and the top is removed; and (2) cross-cutting in the felling area (s)—measurement of the length of the wood pieces and stem cross-cutting: begins when the assistant measures the log length from the bottom of the tree and marks the cross-cutting spots and ends when the feller finishes the last of the cross-cutting and starts toward the next tree to be felled.

The time consumed for each operation, stage, and activity was measured in seconds by using the continuous timing method [44]. The duration of a work shift was measured with the help of a wrist watch. The duration of a work shift started from the moment the team left for the felling area landing and lasted until the team came back to the same place. The cross-cut diameters were measured with the help of the forest caliper that had an accuracy of 1 cm, and the lengths of the tree stem and cross-cut logs were measured with the forest tape, which had an accuracy of 10 cm. The field research team was made up of two members: one that measured the work time and another that measured the diameter and resulting wood pieces.

2.3. Data Analysis

Sample size determination represented the first step in the statistical analysis. The number of measurements needed was established by using the relation suggested by [36]:

$$n = \frac{p \cdot q \cdot t^2}{e^2} \tag{1}$$

where n is the minimum number of measurements, p is the percentage of unproductive time, q is the percentage of active time, t is the value of Student's distribution ($t = 1.96$), and e is the maximum admitted error.

The values for the p and q parameters were established by trial measurements. The minimum number of measurements was established for a significance level of 95% and maximum admitted error of 10%. The concrete situation, namely the number of measurements needed and those actually made, is presented in Table 3.

Table 3. Minimum number of measurements.

Operation	Venue	No. of Trees Used for p and q Determination	Parameter Values (%)		No. of Measurements (Trees)	
			p	q	Calculated	Made
Delimbing and cross-cutting	Felling area	48	36	64	89	148

Note: p—the percentage of unproductive time; q—the percentage of active time.

The establishment of the time consumption structure, which shows the share of each stage and activity in the operations analysed and the correlation of the time consumption with the characteristics of the marked trees, imposed a minimum number of 89 trees to be felled in the felling area for the conditions under which the research was conducted (Table 3). The larger number of actual measurements made (148) was adopted out of a need to assure a normal distribution of trees according to the diameter categories and to meet the requirements stating that for each diameter category at least five trees should be measured [45]. A selection of trees and pieces analysed was not made in order to not interfere with normal working conditions. A work schedule was established by the chainsaw operators and all of the trees and pieces cut in one shift were registered.

The work time structure corresponding to each operation was established by taking into consideration the time consumption for each work stage. The share of work time consumed for delimbing and tree cross-cutting in the felling area was determined. The work performance and productivity were calculated by considering the time consumption with the following variants: (i) for primary processing of felled trees—work productivity (PM) expressed in $m^3 \cdot h^{-1}$ and trees$\cdot h^{-1}$, which was calculated based on the real work time (time element MW—main work time); and work performance (Pm) expressed in $m^3 \cdot h^{-1}$ and trees$\cdot h^{-1}$, which was calculated based on the total work time (TT); and (ii) for cross-cutting in the felling area—chainsaw productivity (Pf), which was calculated as a ratio of the cross-cut surface to the real cross-cutting time (Ts(MW)) and expressed in $cm^2 \cdot s^{-1}$. The main statistical indicators (mean, standard error, median, standard deviation, and variation coefficient) of the chainsaw performance, productivity variations, and measured variables were determined.

The normal distribution of data has been checked by using the Kolmogorov—Smirnov test for a transgression probability of 5%. In all situations, normal distributions were found. Furthermore, the relationships between the work time or productivity and independent variables were studied by using ANOVA, and simple and multiple linear regressions. The regression significance was tested with Fisher's F-test, while the significance of the independent variable coefficients was tested using Student's t-test for a transgression probability of 5%, 1%, and 0.1%. The correlation intensity, expressed by the absolute value of the correlation coefficient, was estimated using the scale from [46]: 0 to 0.19—very weak; 0.20 to 0.39—weak; 0.40 to 0.59—moderate; 0.60 to 0.79—strong; and 0.80 to 1.0—very strong.
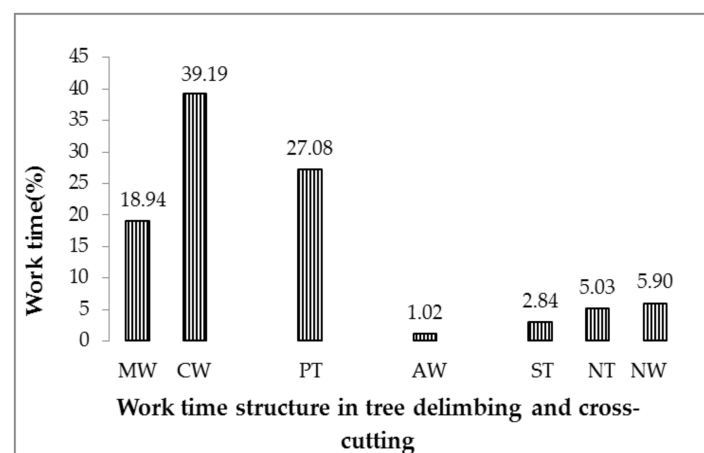
3. Results and Discussion

A total of 148 trees were delimbed and cross-cut in a TT of 2824.96 min. The work time structure considered in this research for delimbing and cross-cutting is presented in Table 4.

Detailed knowledge of the work time structure is extremely important as the time elements show the work time distribution for the activities. Thus, activities can be planned in such a way that the time consumption can be reduced. The work time structure demonstrated that productive time (PW) accounted for 58.13% (MW accounted for 18.94%), preparatory time (PT) accounted for 30.94% (including delays—service time (ST) which accounted for 2.84%), non-work time (NT) accounted for 5.03%, and non-workplace time (NW) accounted for 5.90% of the TT. An important part in the work time structure (13.77%) was represented by the delays, which are considered part of the ST (2.84%), NT (5.03%), and NW (5.9%). Maintenance and fuelling ensure that the chainsaw works within the optimum parameters and, as a result, delays are difficult to reduce. This is also true for the delays included in the NW, which are caused by going to the felling area when the schedule begins and back home when the schedule ends. Delays included in the NT (personal, operational, and technical delays) can be reduced by better organization and planning of operations. The detailed structure of the work time during delimbing and cross-cutting in the felling area is presented in Figure 1.

Table 4. Work time structure for delimbing and cross-cutting.

| No. of Trees | Volume | Work Place Time (WP) | | | | | | Non-Workplace Time (NW) | | Total Time (TT) | |
		Productive Work Time (PW)		Supportive Work Time (SW)		Non-Work Time (NT)					
	m^3	$s \cdot m^{-3}$	%	$s \cdot m^{-3}$	%	$s \cdot m^{-3}$	%	$s \cdot m^{-3}$	%	$s \cdot m^{-3}$	%
148	316.038	311.77 $s \cdot tree^{-1}$ 665.76	58.13	165.94 $s \cdot tree^{-1}$ 354.34	30.94	26.97 $s \cdot tree^{-1}$ 57.59	5.03	31.64 $s \cdot tree^{-1}$ 67.57	5.90	536.32 $s \cdot tree^{-1}$ 1145.26	100

Figure 1. Work time structure in primary processing of felled trees in felling areas: MW—main work time; CW—complementary work time; PT—preparatory time; AW—ancillary work time; ST—service time; NT—non-work time; NW—non-workplace time.

The time consumed for the primary processing of one tree in the felling area was 1145.26 s, and the time consumed for the primary processing of 1 m^3 of wood in the felling area was 536.32 s. The literature contains mathematical models used for the estimation of the time consumed, as well as the factors that influence the time consumption. [24] used an exponential model to determine the time used for delimbing in spruce tree stands depending on the crown size expressed with the help of the dbh. In this case, the time consumed increased from 1 min·tree^{-1} for a dbh of 16 cm to 5 min·tree^{-1} for a dbh of 56 cm. [34] showed that the time consumed for cross-cutting pine trees depends more on the length of the wood assortments than on the dbh. Therefore, the time consumed for cross-cutting was inversely proportional to the length of the wood assortments.

The MW was made up of the real work time for delimbing (Ttcv(MW)) to which the real cross-cutting time (Ts(MW)) was added, according to the following relation:

$$MW = Ttcv(MW) + Ts(MW) \tag{2}$$

The results obtained showed that the Ttcv(MW) and Ts(MW) account for 96.18% and 3.82% of the total MW, respectively. Similar relations can be written for the complementary work time (CW), PT, and ancillary work time (AW). The share of delimbing and cross-cutting in the time elements taken into consideration is presented in Figure 2.
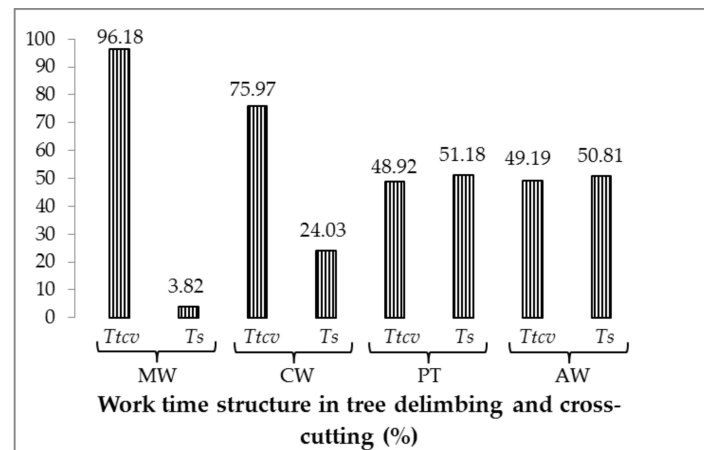
Figure 2. Work time structure according to operations: MW—main work time; CW—complementary work time; PT—preparatory time; AW—ancillary work time; Ttcv—work time consumed for delimbing; Ts—work time consumed for tree cross-cutting.

For 1 m^3 of delimbed and cross-cut wood, the TT was 536.32 s. This time included all of the time elements taken into consideration, which are shown in Figure 3. It should be noted that the work time for delimbing (Ttcv) and work time for cross-cutting trees in the felling area (Ts) each had one component in the MW, CW, PT, and AW. For the ST, NT, and NW, the components of the Ttcv and Ts could not be determined. The activities corresponding to these time elements do not focus directly on delimbing and cross-cutting, but more on providing optimum work conditions for workers. These conditions are needed for a normal development of the production process and proper functioning of the equipment. Therefore, as can be seen in Figure 3, the time required for delimbing (Ttcv) and cross-cutting (Ts) in the felling area, as well as the total work time (TT), can be calculated by using the following relations:

$$Ttcv \ [s \cdot m^{-3}] = Ttcv(MW) + Ttcv(CW) + Ttcv(PT) + Ttcv(AW) \tag{3}$$

$$Ts \ [s \cdot m^{-3}] = Tts(MW) + Tts(CW) + Tts(PT) + Tts(AW) \tag{4}$$

$$TT \ [s \cdot m^{-3}] = Ttcv + Tts + ST + NT + NW \tag{5}$$

Tree size is one of the main characteristics influencing tree felling and processing with a chainsaw. The time consumed for the primary processing of felled trees increased as a function of the stem size [26]. Most studies use dbh as the main factor for estimating the productivity and work time by either linear equations [25,33,47,48] or the power function [27,49] and stump diameter in an exponential model [24].

In this research, simple and multiple linear regressions were used to identify the tree characteristics that influenced the work time. Figure 4 presents Ttcv and Ts variations expressed in s·tree^{-1} and s·m^{-3}, depending on the tree diameter class. When the Ttcv and Ts were expressed in s·tree^{-1}, the correlation

intensity between them and the dbh was very strong ($r > 0.9$ in both cases). Consequently, as the tree dbh increased, the time consumed for delimbing and cross-cutting also increased. When the Ttcv and Ts were expressed in $s \cdot m^{-3}$, the correlation intensity between the dbh and Ttcv was moderate ($r = 0.54$), while the correlation intensity between the dbh and Ts was strong ($r = 0.79$). Thus, the Ttcv and Ts were inversely proportional to the dbh when the time consumed was expressed in $s \cdot m^{-3}$ and directly proportional when the time was expressed in $s \cdot tree^{-1}$.
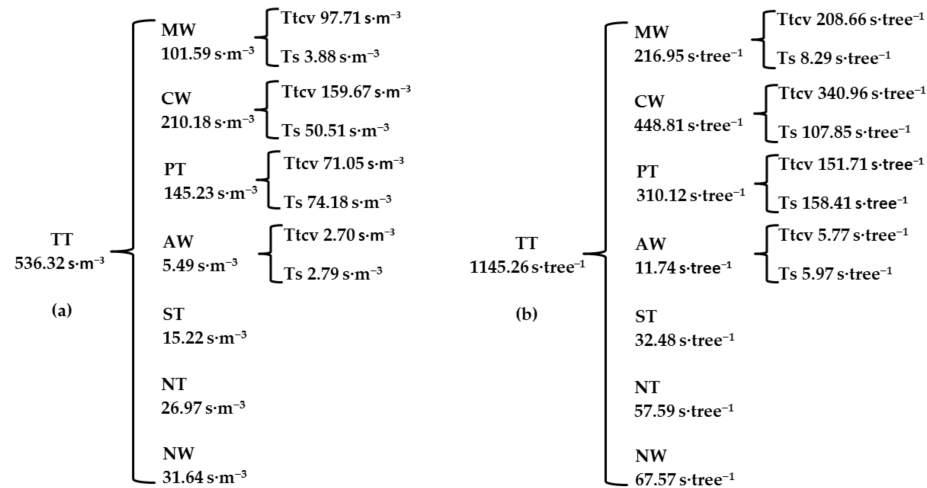
Figure 3. Total work time structure: (**a**) times are expressed in $s \cdot m^{-3}$; (**b**) times are expressed in $s \cdot tree^{-1}$.
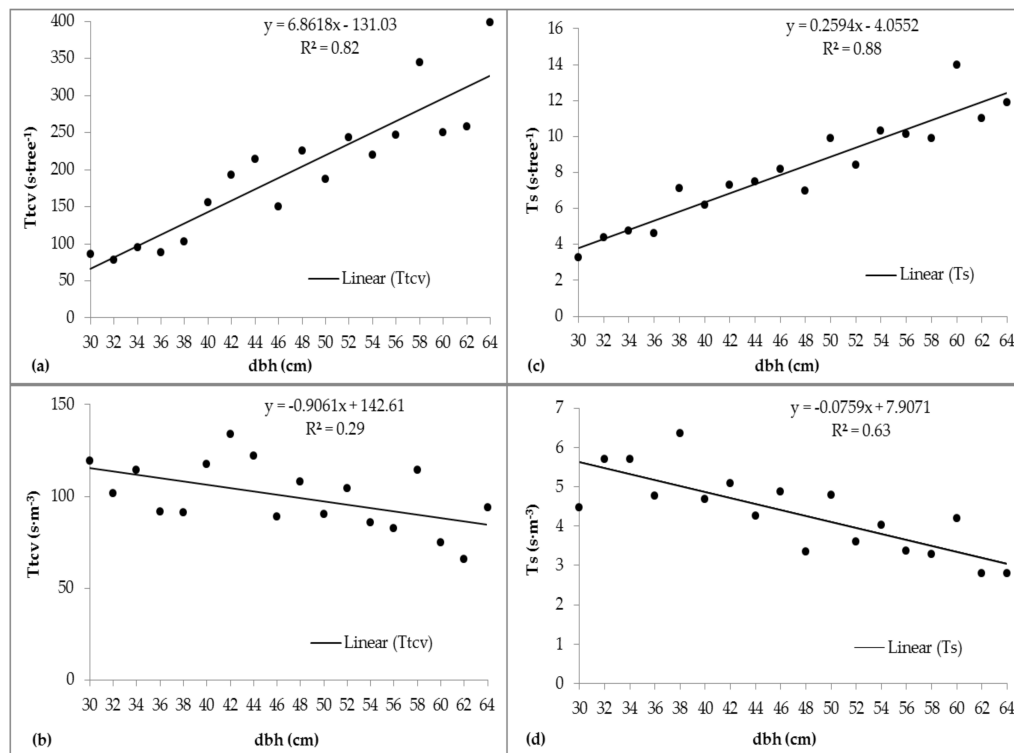
Figure 4. Work time consumed for delimbing (**a**) ($s \cdot tree^{-1}$) and (**b**) ($s \cdot m^{-3}$)) and work time consumed for tree cross-cutting in the felling area (**c**) ($s \cdot tree^{-1}$) and (**d**) ($s \cdot m^{-3}$)) depending on the dbh.

Tables 5 and 6 present the linear regressions that show the intensity of the correlation between the Ttcv, Ts, dbh, l, and V. The analysis of the correlations between the Ttcv, Ts, and dbh demonstrated that the correlation intensity was stronger for both Ttcv versus dbh ($r = 0.65$) and Ts versus dbh ($r = 0.67$). In both situations, the influence of the dbh on the Ttcv and Ts was very significant ($p < 0.001$). The Ttcv and Ts also increased with an increase in the l. When analysing the relationship between the Ttcv, Ts, and l, it was found that, in both situations, the l very significantly influenced the Ttcv and Ts variations ($p < 0.001$). The correlation intensity was moderate in the case of Ttcv versus l ($r = 0.59$) and weak in the case of Ts versus l ($r = 0.37$).

The influence of the independent variables dbh and l on the Ttcv and Ts variations was also analysed using multiple linear regression. The results demonstrated that, as was expected, the dbh influenced the Ttcv and Ts very significantly ($p < 0.001$). In contrast, the l significantly influenced the Ttcv and Ts variation ($0.01 < p < 0.05$). The research also proved that the V very significantly influenced the Ttcv and Ts ($p < 0.001$). An analysis of the correlation between the Ttcv, Ts, and independent variable V was justified because most often the V plays a very important role in planning and organizing wood harvesting operations and norms are most often expressed in relation to it.

Table 5. Linear regression analysis of the work time consumed for delimbing in relation to the breast height diameter, stem length, and tree volume.

	ANOVA			Significance of Variable Coefficient				
R^2	Standard Error	Degrees of Freedom	F	Variable	Coefficient	Standard Error	t Statistic	*p*-value
Simple linear regression analysis of Ttcv in relation to dbh								
0.43	87.941	Regression 1 Residual 146	108.615 ***	Constant dbh	−184.758 8.206	38.435 0.787	−4.807 10.422	<0.001 *** <0.001 ***
Simple linear regression analysis of Ttcv in relation to l								
0.35	93.812	Regression 1 Residual 146	77.739 ***	Constant l	−215.672 17.626	48.741 1.999	−4.425 8.817	- <0.001 ***
Simple linear regression analysis of Ttcv in relation to V								
0.44	87.271	Regression 1 Residual 146	112.536 ***	Constant V	45.342 76.483	16.985 7.210	2.669 10.608	<0.01 ** <0.001 ***
Multiple linear regression analysis of Ttcv in relation to dbh and l								
0.45	86.746	Regression 2 Residual 145	58.337 ***	Constant dbh l	−240.609 6.128 6.457	45.337 1.208 2.874	−5.307 5.075 2.247	<0.001 *** <0.001 *** <0.05 *

Note: Asterisks denote F significance and significant correlations: $0.01 < $ *p*-value * < 0.05; $0.001 < $ *p*-value ** < 0.01; *p*-value *** < 0.001; Ttcv—time consumed for delimbing in the felling area; dbh—breast height diameter; l—stem length; V—tree volume.

Considering the results obtained, it was determined that the tree characteristics (dbh, l, and V) can be used as linear models for estimating the Ttcv and Ts. The variation of the Ttcv and Ts was influenced not only by the aforementioned variables, but also by other factors whose influence is difficult to quantify using linear regression. Steep terrain makes the movement of the operators and felling more difficult than in the case of gentle terrain; therefore, the productivity of felling and cross-cutting on gentle terrain is higher than on steep and uneven terrain [33]. The ground slope in the felled tree area also influences the work time because of the posture of the chainsaw operator during work [50]. The work time is also influenced by the presence or absence of seedlings, stumps, rocks, and other items near the felled tree. Low temperatures decrease productivity as the chainsaw operator has to wear thick clothes that hamper movement related to delimbing and stem cross-cutting. Also, low temperatures make the arms, legs, and fingers of the operator stiffer than under normal temperatures (10 °C) [51].

The Pm in the primary processing of felled trees in the felling area was 6.716 m^3·h^{-1} (3.14 tree·h^{-1}). The work performance variation depending on the diameter classes (Figure 5) was established by

considering the total work time measured, which is as presented in Figure 1. The correlation intensity between the Pm and dbh was strong ($r = 0.60$) and very strong ($r = 0.90$). Here, the dbh distinctly and significantly influenced the Pm expressed in tree·h^{-1} ($p < 0.001$) and very significantly influenced the Pm expressed in m^3·h^{-1} ($0.001 < p < 0.01$).

Table 6. Linear regression analysis of the work time consumed for tree cross-cutting in relation to the breast height diameter, stem length, and tree volume.

	ANOVA			Significance of Variable Coefficient				
R^2	Standard Error	Degrees of Freedom	F	Variable	Coefficient	Standard Error	t Statistic	*p*-value
		Simple linear regression analysis of Ts in relation to dbh						
0.44	2.403	Regression 1 Residual 146	117.859 ***	Constant dbh	−2.916 0.234	1.050 0.022	−2.766 10.856	<0.01 ** <0.001 ***
		Simple linear regression analysis of Ts in relation to l						
0.14	2.994	Regression 1 Residual 146	24.043 ***	Constant l	0.753 0.313	1.555 0.064	0.484 4.903	- <0.001 ***
		Simple linear regression analysis of Ts in relation to V						
0.33	2.650	Regression 1 Residual 146	71.011 ***	Constant V	4.344 1.845	0.516 0.219	8.423 8.427	<0.001 *** <0.001 ***
		Multiple linear regression analysis of Ts in relation to dbh and l						
0.49	2.313	Regression 2 Residual 145	69.998 ***	Constant dbh l	−0.555 0.321 −0.273	1.209 0.032 0.077	−0.459 9.985 −3.563	- <0.001 *** <0.001 ***

Note: Asterisks denote F significance and significant correlations: $0.01 < $ *p*-value * < 0.05; $0.001 < $ *p*-value ** < 0.01; *p*-value *** < 0.001; Ts—time consumed for cross-cutting in the felling area; dbh—breast height diameter; l—stem length; V—tree volume.
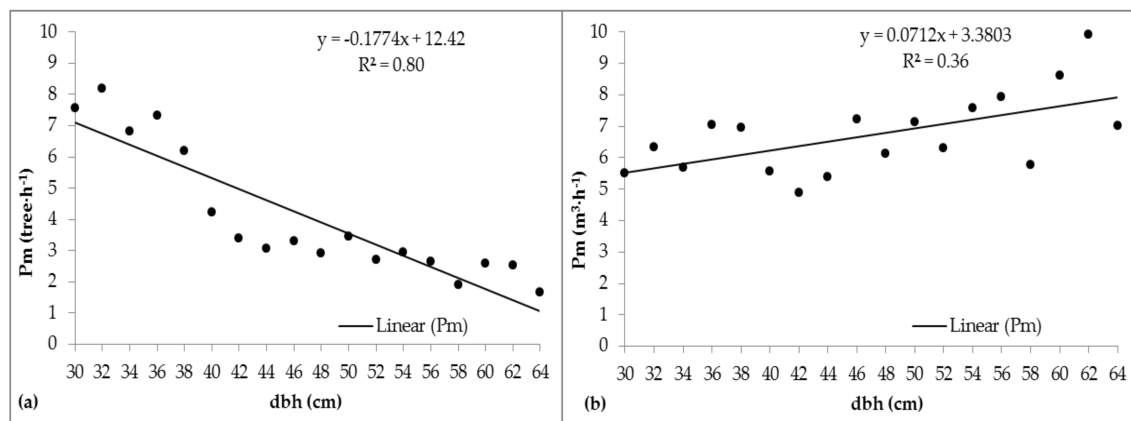
Figure 5. Pm variation according to the dbh: (**a**) expressed in tree·h^{-1}; (**b**) expressed in m^3·h^{-1}.

The calculation of the PM was based on the MW. It represented an important estimation of the Pm, knowing that the MW accounts for 18.94% of the TT. In this case, the PM was 35.459 m^3·h^{-1} (16.58 tree·h^{-1}). The main statistical indicators of the Pm and PM are presented in Table 7.

During cross-cutting, the Pf of the chainsaw was 82.29 cm^2·s^{-1}. Table 8 presents the Pf during cross-cutting in the felling area with the main statistical indicators of variation, which are the cross-cutting time and cross-cut section diameter.

Table 7. Statistical indicators of the performance variation and work productivity in the primary processing of felled trees.

Descriptive Statistics	Mean	Median	Standard Error	Standard Deviation	Variation Coefficient (%)
Descriptive statistics of (P_m)					
P_m [tree·h^{-1}]	3.14	3.06	0.50	2.11	51.78
P_m [m^3·h^{-1}]	6.716	6.650	0.30	1.27	18.86
Descriptive statistics of (P_M)					
P_M [tree·h^{-1}]	16.58	16.16	2.64	11.14	51.78
P_M [m^3·h^{-1}]	35.459	35.111	1.58	6.71	18.86

Note: P_m—Work performance in primary wood conversion in the felling area; P_M—Work productivity in primary wood conversion in the felling area.

Table 8. Statistical indicators of the chainsaw productivity variation in wood cross-cutting in the felling area.

Descriptive Statistics	Mean	Median	Standard Error	Standard Deviation	Variation Coefficient (%)
Descriptive statistics of chainsaw productivity (Pf)					
Pf [cm^2·s^{-1}]	82.29	82.18	2.16	26.29	31.95
Descriptive statistics of Ts (MW) and dc					
Ts [s]	8.28	8.00	0.26	3.22	38.87
dc [cm]	28.43	28.00	0.56	6.78	23.87

Note: Pf—chainsaw productivity; Ts (MW)—real cross-cutting time; dc—cross-section diameter.

A very strong direct correlation ($r = 0.87$) existed between the Pf and diameter of the cross-cut sections (dc), with the latter influencing the Pf variation very significantly (Table 9).

Table 9. Linear regression analysis of the chainsaw productivity in relation to the cross-section diameter.

	ANOVA				Significance of Variable Coefficient				
R^2	Standard Error	Degrees of Freedom	F	Variable	Coefficient	Standard Error	t Statistic	p-value	
Simple linear regression analysis of Pf in relation to dc									
0.76	9.462	Regression 1	50.150 ***	Constant	8.216	10.345	0.794	-	
		Residual 16		dc	1.522	0.215	7.082	<0.001 ***	

Note: Asterisks denote F significance and significant correlations: $0.01 < p$-value * < 0.05; $0.001 < p$-value ** < 0.01; p-value *** < 0.001; Pf—chainsaw productivity; dc—cross-section diameter.

The chainsaw Pf was 82.29 cm^2·s^{-1}. The results obtained showed that the Pf was determined by the dc with an R^2 of 0.76. Previous research demonstrated that the Pf also varies depending on the parameters of the chainsaw, namely the carburetor type, engine revolution, guide bar type, chain pitch, and cutter angle [52]. A high emphasis is placed on the chainsaw operating at the optimum functioning parameters and appropriate chain sharpening [53]. Chainsaw work techniques that are always dependent on the dc and guide bar length may also influence the Pf. Therefore, the skills and abilities of the chainsaw operator are another influencing factor. Working conditions in the felling area, including the slope and wood tension, are factors that also influence the Pf.

The development of mathematical models for determining the Pm and PM with a chainsaw helps forest managers select human resources and materials needed for work planning to fit a certain time frame dedicated to wood harvesting. The impact on the forest ecosystem should always be

minimized. The productivity models and work time structure used in this research can also be useful in the development of simulations and training of chainsaw operators.

This research methodology was based on the use of a single team of workers. Therefore, the results obtained do not show the variations that may be caused by the human factor. It is well known that the operators have a large influence on the productivity in most types of forest work [54]. In comparative time studies, it is difficult to provide exactly the same conditions. Out of all of the factors that influence the time consumption, the most difficult to keep constant is the operator [54]. The present methodology can also be used with other harvestable tree-stands. New results obtained can be compared with the ones presented in this paper, as well as with those displayed in other papers obtained under similar conditions.

4. Conclusions

The results obtained and comparisons with other similar studies justified the necessity of studying delimbing and cross-cutting as operations distinct from tree felling.

Tree size was one of the main characteristics that influenced tree processing with a chainsaw. Thus, the dbh, l, and V may be used in simple and multiple linear models for estimating the work time required for delimbing and cross-cutting.

The research methodology used in this paper, which was based on the use of a single work team, and work time structure represented both a new approach to this problem and allowed for the identification of time elements and factors that influence their variation.

The development of mathematical models for determining the work productivity during the primary processing of felled trees with a chainsaw can help forest managers select human resources and materials needed for work planning to fit a certain time frame dedicated to wood harvesting.

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