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European Beech Log Sawing Using the Small-Capacity Band Saw: A Case Study on Time Consumption, Productivity and Recovery Rate

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Abstract: In rural, isolated areas, sawmills are often equipped with one or more small-capacity hand-fed band saws. Even in this situation, the productivity of the band saw must be viewed through the factors that influence it, namely the characteristics of logs and the optimization of the stages and activities carried out. Therefore, time consumption, the structure of working time and the recovery rate in sawing logs into lumber provide important information for users. The structure of the sawing operation for a work team made up of an operator and an assistant was divided into six work stages. The sawing pattern used involves sawing the log up to approximately half of the diameter, then rolling the log with 180° and continuing the sawing, aiming to obtain lumber with a thickness of 40 and 50 mm from the central part of the log. The productivity was 2.45 $m^3 \cdot h^{-1}$, the recovery rate was 70.84% and the working time real-use coefficient was 0.37. Research has highlighted the positive correlation between working time and the middle diameter of the logs (R^2 = 0.84). The feeding speed was also determined along with the quality of cuts, which was expressed by the thickness uniformity of the lumber and the presence of cutting teeth traces on the newly created surfaces.

Keywords: lumber; band saw; productivity; working time structure; recovery rate

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1. Introduction

In Romania, European beech (*Fagus sylvatica* L.) is the most widespread species, occupying about 33.4% of the national forest surface which amounts to 6.604 million hectares, representing 27.7% of the country's surface [1]. Beech forests are found in the Carpathian Mountains, starting from altitudes of 300 m to altitudes of 1400 m [2]. In 2020, 19.7 million cubic meters of wood were harvested from Romanian forests, of which 6.110 million cubic meters (31%) was beach wood [1]. The wood is harvested by 5185 accredited logging companies. In 2020, about 64.1% was harvested from forests owned by the state, 32.3% from private forests and 3.6% from forest vegetation located on lands outside the forest [1]. Individual owners may harvest at most 20 $m^3 \cdot year^{-1}$ of the total forest that they own. Private properties represent 51.9% of the national forest surface [1]. In 2011, there were approximately 830,000 private properties, 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 restitution process is not over yet and there are still numerous lawsuits taking place. It may be estimated though that when the restitution process is over, state-owned forests will represent about 40% of the national forest surface [3,4].

In [5], it is mentioned that there are about 7000 wood processing factories that produce about 4.47 million m^3 of lumber annually, many of them being of small capacity, with a production of 8–10 m^3 per day. Taken together, the forestry and wood processing industries have a contribution of 3.5% to the country's GDP, representing an important branch of the economy in which approximately 128,000 employees are working, while another 186,000 are working in related sectors [6]. Sawmills that have a small sawing capacity of up to

5000 $m^3 \cdot year^{-1}$ of beech logs often use one or more band saws with a sawing capacity of 4–8 $m^3 \cdot shift^{-1}$. In Romania, small sawmills are important components of the industry because they substitute large sawmills in the market conditions in which the latter could not operate feasibly [7]. They use logs with unproductive dimensions and characteristics for large factories, they supply the local market, substitute imports, provide jobs and bring revenues to local budgets through the sale of manufactured products [8,9]. Moreover, the purchase cost is low, which is an important aspect especially in rural areas. One such piece of equipment is the band saw FBO–03–CUT, used in the present article and made in Romania by S.C. Cutean Company Srl.

In general, in the literature of the field, the articles published address two main aspects: (i) the study of the productivity of machinery and the factors on which the latter depends [5,7,10,11]; and (ii) worker health and safety, risk factors, accidents and occupational disease analysis [7,12–15]. The purpose of the present article falls within the first direction of research and is represented by the determination of time consumption and productivity of the FBO–03–CUT band saw when sawing beech logs into lumber, in order to optimize activities and increase work productivity.

2. Materials and Methods

2.1. Field Data Collection and Equipment

The research was carried out in a beech lumber factory from Buzău county, which has as its object of activity for the processing of beech wood, the final product being beech lumber. The measurements took place at the end of February 2021, the beech logs being partially frozen.

To achieve the goal of this paper, the research methodology had to respond to the following challenges: (1) description of the band saw used for sawing logs into lumber; (2) description of the work team and the work tasks of each worker; (3) establishment of a work time structure by stages and activities that allow for the grouping of activities carried out when sawing logs into lumber; and (4) the determination of productivity, recovery rates, coefficient of use of the working time and feeding speed of the band saw.

The band saw FBO–03–CUT is a horizontal one, with manual advance, intended for sawing logs into lumber and into beams up to 160 mm thick, with a maximum length of 7.5 m (Figure 1).

FBO–03–CUT is operated by two workers, an operator and an assistant. The operator carries out the following activities: together with the assistant, he or she feeds the band saw platform with logs and fixes the log with clamps; adjusts the lumber thickness; ensures the advance of the saw; gives instructions to the assistant so that the rolling logs correspond to the sawing scheme used; changes the cutting blade at regular time intervals or when the situation requires it; and informs the technical team if the band saw is not working properly. The assistant participates in feeding the platform, rolls the logs according to the instructions received from the operator, fixes the logs on the platform and manually removes lumber and sawdust from the sawing area.

In the research undertaken, the sawing pattern used involves sawing the log up to approximately half of the diameter, then rolling the log with 180° and continuing the sawing, aiming to obtain lumber with a thickness of 40 and 50 mm from the central part of the log. Toward the periphery of the section, the log was sawed into lumber with a thickness of 25 mm (Figure 2).

Figure 1. The band saw FBO–03–CUT.

Figure 2. The sawing pattern used for sawing beech logs.

The consumption of working time and its structure was analyzed at the level of stages and activities. Activities which were strictly necessary from a technological point of view for the normal development of the production process were considered work stages. To these, a series of activities which were not absolutely necessary from a technological point of view was added. Their acceptance was justified in order to ensure the conditions imposed by work safety norms, ergonomic, physical and physiological requirements [16].

The structure of the sawing operation for a piece of lumber, for the work team made up of an operator and an assistant, was divided into six work stages according to Table 1. The activities specific to each stage are presented in Table 2.

Table 1. Stages in the sawing operation.

Stage	Symbol	Begins	Ends
1. Loading and fixing the log on the band saw platform	*LFL*	When the operator and assistant start feeding a new log to the band saw platform	When the operator and assistant have finished clamping the log to the band saw platform
2. Slabs sawing	*SS*	When the operator manually moves the band saw	When the slabs are detached from the log
3. Setting the thickness of the lumber/slabs	*STL*	When the operator sets the lumber thickness adjustment mechanism	When the operator has finished setting the thickness of the lumber
4. Lumber sawing	*LS*	When the operator manually moves the band saw	When the piece of lumber is completely detached from the log
5. Lumber evacuation	*LE*	When the assistant removes the sawdust from the piece of lumber	When the piece of lumber reaches the conveyor that feeds the circular edging saw
6. Returning the band saw to the start position	*RBS*	When the operator begins to move the band saw to the starting position	When the band saw reaches the starting position and the sawing cycle can be resumed

Table 2. Working time structure for sawing beech logs (adapted from [17]).

Working Time Structure					Operation	Stage	Activity
WP	*NT*				Log sawing	-	Delays caused by meals, breaks, rest, personal needs and organization
	WT	*PW*	*MW*			*SS*	Slab sawing
						LS	Lumber sawing
			CW			*STL*	Setting the thickness of the lumber/slabs
						LE	Removal of sawdust from the piece of lumber; Lumber evacuation
						RBS	Returning the band saw to the start position
		SW	*PT*	*SU*		*LFL*	Loading and fixing the log on the band saw platform; Rolling the log corresponding to the sawing pattern and fixing it with clamps
			ST	*MT*		-	Changing the cutting blade

Note: *WP*—workplace time; *NT*—non-working time; *WT*—working time; *PW*—productive working time; *SW*—supportive working time; *MW*—main working time; *CW*—complementary working time; *PT*—preparatory time; *SU*—set-up time; *ST*—service time; *MT*—maintenance time.

Time was measured in seconds, by using the continuous time study method. A stopwatch was used to measure time by recording the beginning and the ending of each stage or activity. The time for delays and their causes (change of cutting blade, adjustments of the band saw, removal of sawdust from the area of the band saw, meal break, personal needs, rest, etc.) were also measured.

After sawing each piece of lumber, the minimum width of each piece on the narrowest face and the thickness at the ends of the piece and in the middle were measured. The minimum width was measured with a tape measure, and it corresponded to the width of the edged lumber. The thickness was measured with a caliper, both measurements being expressed in millimeters. Thus, based on the width and the average thickness of the lumber pieces, their volume was calculated. The quality of the cut was also evaluated, observing the presence of cutting teeth marks on the faces of the timber pieces and the uniformity of the thickness of timber pieces.

2.2. Data Analysis

Ensuring the statistical representativeness of the research conducted is the first step in data analysis. For this, the economic agent was asked about the size of the lot of logs that were to be sawed using the above-mentioned sawing pattern. The answer to the question was about 50 m^3, representing 94 beech logs with mid-diameters between 35 and 70 cm, and lengths between 2.70 and 3.60 m according to SR 2024-1993 (the national standard regarding the dimensions and quality of beech logs for lumber). In order to determine the minimum number of logs subjected to measurements, it was necessary to determine the coefficient of variation of the mid-diameter. The mid-diameters were measured for 30 logs, the calculated coefficient of variation being 22.95% (Table 3).

Table 3. Characteristics of logs and resulting lumber. Statistical indicators of the mid-diameter of average logs and the recovery rate.

No. Log	Log Characteristics			Log Volume	Number of Cuts	Lumber Volume	Recovery Rate
	Length	Mid-Diameter					
	m	cm	Statistical Indicators	m^3	no.	m^3	%
1	3.6	47		0.625	9	0.396	63.39
2	3.0	53		0.662	11	0.464	70.07
3	2.9	68		1.053	14	0.846	80.29
4	3.3	45		0.525	10	0.414	78.85
5	3.0	40		0.377	9	0.278	73.82
6	3.0	45		0.477	11	0.370	77.61
7	3.4	35		0.327	9	0.184	56.35
8	2.7	36		0.275	8	0.160	58.24
9	3.1	66		1.061	14	0.894	84.33
10	2.8	42		0.388	9	0.260	66.94
11	4.0	49	Mean mid-diameter (cm)—47.03;	0.754	10	0.641	85.01
12	3.0	62	Standard deviation—10.794;	0.906	11	0.750	82.81
13	3.0	40	Variation coefficient (%)—22.95;	0.377	7	0.259	68.71
14	3.0	52	Minimum (cm)—35;	0.637	11	0.484	76.01
15	3.2	52	Maximum (cm)—68;	0.680	11	0.460	67.66
16	3.1	39	Mean recovery rate (%)—70.84;	0.370	9	0.278	75.03
17	3.2	36	Standard deviation—9.891;	0.326	9	0.174	53.31
18	3.0	61	Variation coefficient (%)—13.96;	0.877	14	0.750	85.52
19	3.4	45	Minimum (%)—53.31;	0.541	9	0.368	68.12
20	2.9	35	Maximum (%)—85.52;	0.279	8	0.173	62.11
21	3.2	35		0.308	8	0.185	60.24
22	3.0	40		0.377	9	0.278	73.75
23	3.2	38		0.363	9	0.292	80.53
24	3.0	66		1.026	14	0.832	81.05
25	2.7	66		0.924	14	0.778	84.27
26	3.2	35		0.308	9	0.169	54.83
27	3.2	52		0.680	11	0.461	67.89
28	2.8	37		0.301	8	0.165	54.74
29	3.1	41		0.409	9	0.273	66.70
30	3.0	53		0.662	11	0.424	64.05
Total				16.873	-	12.461	73.86

Further, the number of necessary measurements was established by using the relation suggested by [18]:

$$n = \frac{u^2 \cdot S_{\%}^2 \cdot N}{N \cdot \Delta_{\%}^2 + u^2 \cdot S_{\%}^2} \quad (1)$$

n—the minimum number of logs that will be sawed;
u = 1.96—the standard deviation of normal distribution, corresponding to the transgression probability α = 5%;

$S\%$ = 22.95%—the variation coefficient of the middle diameter for the logs analyzed;
$\Delta = \pm 10\%$—the limit error;
N = 94—the total number of logs in the lot intended for sawing.

Knowing the parameters that come into play when establishing the number of sample pieces, by applying the above formula, a log number—n = 17—was obtained. Because $n < 30$, the result obtained was considered a temporary value n', n being recalculated with the same formula where u is replaced by t (t Student distribution) [18]. The value of t is determined according to the number of freedom degrees $f = n' - 1$ and according to α. At 16 freedom degrees and $\alpha = 5\%$ it yields that $t = 2.120$.

By applying the formula again, a number of 19 logs was obtained. A great number of measurements were made (30 logs, those for which the coefficient of variation of the mid-diameter was determined) in order to normalize the distribution of the values measured and minimize the Hawthorne effect.

Productivity defined as the ratio of input to output [19–21], is a synthetic indicator which defines the production capacity level of use in a system under certain work conditions and it is expressed, in log sawing, usually in the following form $m^3 \cdot h^{-1}$, respectively:

$$W = \frac{V}{TU} \tag{2}$$

W—the productivity;
V—the log volume sawed in a time unit (m^3);
TU—the time unit taken into consideration (hour, work shift, etc.).

Furthermore, by dividing the working time corresponding to the LS and SS stages by the workplace time, the working time real-use coefficient (K) when sawing the logs could be established [10]:

$$K = \frac{TLS + TSS}{WP} \tag{3}$$

K—the working time real-use coefficient;
TLS—the working time consumed in the LS stage;
TSS—the working time consumed in the SS stage;
WP—workplace time.

The recovery rate, when logs are sawed into lumber, was expressed as a percentage representing the ratio of the volume of lumber obtained to the volume of sawed logs [11,22,23]:

$$RR = \frac{V_{lumber}}{V_{logs}} \cdot 100 \tag{4}$$

RR—the recovery rate (%);
V_{lumber}—the volume of lumber obtained (m^3);
V_{logs}—the volume of sawed logs (m^3).

The feeding speed was calculated in two ways: (1) as a ratio of the cumulative length of the lumber pieces resulting from a log to the working time TLS, corresponding to the LS stage being expressed in $m \cdot min^{-1}$; (2) as a ratio of the cumulative area of the sawing cuts to the working time TLS, being expressed in $m^2 \cdot min^{-1}$.

Further, the correlation between the working time and mid-diameter of the logs was tested by using the simple linear regression. The statistical interpretation of the regression was done using an ANOVA.

3. Results and Discussion

Based on the working time consumed for the realization of each work stage, the structure of the working time for sawing logs was established (Table 4). Thirty logs totaling to a volume of 16.87 m^3 were sawed. The total working time WP required for sawing the logs was 24,796 s.

Table 4. Working time structure for sawing beech logs.

Number of Logs	**Volume**	***WP***									
		WT								***NT***	
		PW				***SW***					
		MW		***CW***		***PT (SU)***		***ST (MT)***			
	m^3	**s·m**$^{-3}$	**%**	**s·m**$^{-3}$	**%**	**s·m**$^{-3}$	**%**	**s·m**$^{-3}$	**%**	**s·m**$^{-3}$	**%**
30	16.87	542	36.85	463	31.53	260	17.72	143	9.72	61	4.18
Total		1005 s·m^{-3}				403 s·m^{-3}					
Overall Total		1469 s·m^{-3}									

The working time structure, by time elements, is presented in Figure 3.

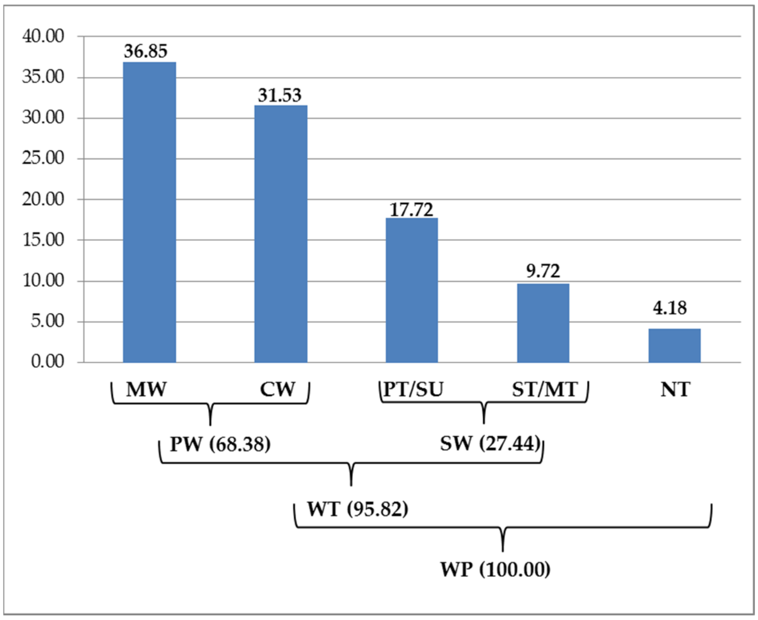

Figure 3. Working time structure according to time elements (%): *WP*—workplace time; *NT*—non-working time; *WT*—working time; *PW*—productive working time; *SW*—supportive working time; *MW*—main working time; *CW*—complementary working time; *PT*—preparatory time; *SU*—set-up time; *ST*—service time; *MT*—maintenance time.

It is observed that the *WT*–*NT* ratio was 96%:4%, indicating the main share of working time. The distribution of working time, by stages, is presented in Figure 4. It can be seen that the *LS* and *LFL* stages have the largest share; together they represent 47.9% of the working time. The *LS* stage represents 30.18% and is explained by the fact that the advance of the band saw is ensured manually through pushing by the operator. Additionally, *LFL* represents 17.72%, this operation being performed manually. In [24], it was stated that the operating time required to feed the saw with logs, turn the logs and fix them in the clamps, can be reduced by the proper training of the workers. A large share is also represented by delays (13.9%) being caused by technical and personal needs.

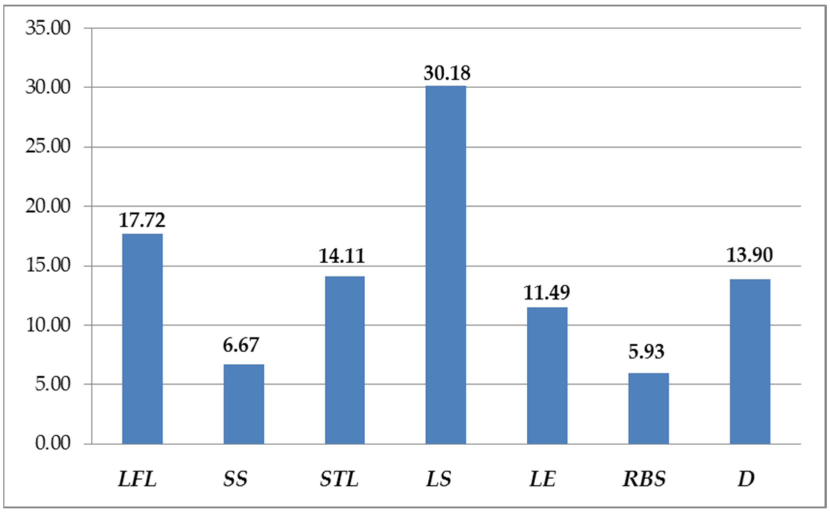

Figure 4. Distribution of working time by stages (%): *LFL*—loading and fixing the log on the band saw platform; *SS*—slab sawing; *STL*—setting the thickness of the lumber; *LS*—lumber sawing; *LE*—lumber evacuation; *RBS*—returning the band saw to the start position; *D*—delays.

Among the dendrometric characteristics of logs, working time best correlates with the mid-diameter (R^2 = 0.84). In [24], similar results were also obtained, where R^2 = 0.702. The link between the two variables was established by the means of simple linear regression, the results being presented in Table 5. Thus, a strong positive correlation was highlighted between the studied variables (0.75 < r < 0.95). In this situation, the coefficient of determination R^2 shows that the dependence of working time on the middle diameter is 84%, 16% of the variation of the working time being caused by other factors.

Table 5. Linear regressions analysis of *WT* in relation to the *dm*.

ANOVA				**The Significance of the Variable Coefficient**				
R^2	**Standard Error**	**Degrees of Freedom**	F	**Variable**	**Coefficient**	**Standard Error**	t **Statistic**	p**-Value**
0.84	144.43	Regression 1 Residual 28	141.50 ***	Constant	−563.54	119.80	−4.70	<0.001 ***
				dm	29.56	2.49	11.90	<0.001 ***

Note: Asterisks denote *F* significance and significant correlations: *p*-value *** < 0.001; *WT*—working time; *dm*—middle cross-section diameter.

The productivity of the FBO–03–CUT band saw was 2.45 $m^3 \cdot h^{-1}$ of the sawed logs, which means that 38.73 $m^2 \cdot h^{-1}$ of lumber was obtained. In a similar study, [10] obtained a productivity of 2.90 $m^3 \cdot h^{-1}$. In [7], it was established that productivity is often influenced by the human factor through its preparation and the decisions made, and by the variable characteristics of the logs with respect to their dimensions and quality, which limit the operation of the band saw at its maximum capacity. The productivity obtained 2.45 $m^3 \cdot h^{-1}$, which is generally higher than in manual mobile band saws 0.64–0.86 $m^3 \cdot h^{-1}$ [25]. Productivity is also influenced by the thickness of the logs. The larger the thickness of the log, the smaller the number of cuts for sawing a log and the higher the productivity [24].

The working time real-use coefficient *K* was 0.37 and falls within the range of 0.3–0.5, specific to the band saws with manual advance [26,27]. According to [10], an increase in the *K* coefficient can be obtained by automating the phases of loading, rolling and fixing the logs and by increasing the speed of the *RBS* stage. By increasing the feeding speed, respectively, by increasing the coefficient *K*, an increase in the productivity of the band saw definitely occurs. However, this increase is not linear; [10] show that for a 100% increase in feeding speed, productivity increased by about 20%. The variable characteristics of the logs in terms of their dimensions and quality influence the feeding speed and thus the working time and the productivity of the machine [28].

In the case of the band saw analyzed, the feeding speed is not constant; it is ensured by pushing the band saw manually and it varies, as previously shown, with the following sawing conditions: the presence of wood defects, the frozen state of the wood, the wear of the cutting blade, etc. Analysis of the results obtained (Table 6) showed that the variation of the feeding speed is higher when it is expressed in $m \cdot min^{-1}$, the coefficient of variation being 39.46%. When the feeding speed is expressed in $m^2 \cdot min^{-1}$, the coefficient of variation is 22.41%. Thus, it can be said that the width of lumber pieces, conditioned by the diameter of the logs, influences the feeding speed. The larger the width of the lumber, the greater the effort made by the operator to manually ensure that the feeding speed becomes lower. Therefore, even though logs of a larger diameter are sawed with a reduced feeding speed, the log band saw achieves a greater capacity and vice versa. The effect of log volume on productivity is greater than the influence of the adjustments in the log feeding speed [24].

Table 6. Descriptive statistics of the variation in the feeding speed.

Descriptive Statistics	Feeding Speed	
	$m \cdot min^{-1}$	$m^2 \cdot min^{-1}$
Mean	9.826	2.339
Standard deviation	3.877	0.524
Variation coefficient (%)	39.46	22.41
Minimum	3.904	1.506
Maximum	16.150	3.696

The average feeding speed obtained in the present case (9.826 $m \cdot min^{-1}$) is intermediate between the feeding speed obtained by [24] (15.40 $m \cdot min^{-1}$) when sawing with a band saw equipped with a hydraulic carriage and [5] (4.74 $m \cdot min^{-1}$) when cutting with a manual mobile band saw.

The recovery rate obtained (70.84%) was high, being determined by the thickness of the lumber (40 and 50 mm thick lumber predominates) and the width of the kerf of 3 mm. Ref. [5] obtains a similar recovery rate between 62 and 74% in beech logs sawed into lumber with a thickness of 30 and 50 mm. If other factors are kept constant, a reduced kerf should increase the recovery rate, since fewer fibers are lost in the form of sawdust [29]. The larger the thickness of the lumber is, the fewer the cuts needed for sawing a log and thus, the higher the recovery rate. Moreover, the log size and quality have a major impact to recovery rate [30]. Losses can also be caused by log quality expressed by the severity of wood defects.

Regarding the quality of the cuts, the presence of the cutting teeth traces was found on the faces of the lumber pieces starting from 3% and reaching up to 10% of the surface of their faces. This is caused by the deviation of the cutting teeth from the set of cutting blade or the vibrations of the blade [31] as a result of the presence of wood defects, the frozen state of the logs, the presence of foreign bodies, low blade tension force etc., associated with manual, uneven feeding speed of the saw when cutting. In general, any asymmetry in the cutting teeth caused by mounting, grinding or damage may result in the generation of a lateral force [32,33] which can cause cutting deviations. This shows that the percentage of the ST time element in the working time structure cannot be reduced. By replacing and maintaining the cutting blade. An appropriate quality of the cut must be ensured, thus reducing the manufacturing defects for the elimination of which lumber pieces must be subjected to in additional processing operations [27]. Regarding the accuracy of the cuts expressed by obtaining pieces of lumber of the same thickness, it was found that a percentage of 5% of the pieces of lumber presented a thickness variation of more than 3 mm between the thicknesses measured at the ends of the piece and those measured in the middle. In general, the cutting precision depends on the size of the cutting forces caused by feeding speed, the thickness of logs [34], the rotation speed, the sharpening of the blade, the setting system of the lumber thickness being sawed [10], the vibrations and the wear of the cutting blade [31]. A decrease in blade stability causes a vibration that leads to side deflection resulting in cutting deviations, surface roughness, wear and the deformation of the blade [35]. Further, the sawing of frozen logs is difficult, because, at temperatures below −10 °C, the sawdust freezes on the cut surfaces and causes severe dimensional inaccuracies [36]. The cutting blade deviation from the sawing plane during the cut also leads to obtaining lumber with an uneven thickness that requires additional processing operations, reducing the recovery rate and increasing production costs [37]. The debarking of logs, the constant feeding speed of the saw and the avoidance of sawing frozen logs would probably have considerably reduced the non-conformities related to the quality of cuts and the variation in the thickness of lumber pieces.

4. Conclusions

In this paper, time consumption, productivity and recovery rate in the process of sawing beech logs into lumber were studied. The results showed that the time consumed when sawing logs into lumber was 1469 $s \cdot m^{-3}$, depending mainly on the mid-diameter of the log (R^2 = 0.84).

The productivity obtained (2.45 $m^3 \cdot h^{-1}$) was influenced by the thickness of the logs, the feeding speed and the operator's decisions and skills. Productivity could be increased by reducing the time spent on manual activities through adequate operator training. Although increasing the feeding speed leads to increased productivity, this possibility is limited to manual band saws.

The recovery rate obtained (70.84%) is high, being determined by the thickness of the lumber, the width of the kerf and by the quality of the logs.

Regarding the quality of the cuts, the presence cutting teeth traces was found on the faces of lumber pieces starting from 3% and reaching up to 10% of the surface of their faces. Additionally, it was found that a percentage of 5% of the pieces of lumber presented a thickness variation of more than 3 mm. Literature in the field, mentions numerous factors that can determine the cutting blade deviation from the sawing plane during the cut or the blade vibration. Among them, specific to this research, is the partially frozen state of the logs.

For beech sawmills that use low-capacity band saws, the results obtained regarding time consumption, productivity, recovery rate and quality of cuts can be used for a better understanding of the factors that influence the above-mentioned characteristics and thus, make the best decisions regarding the design and organization of technological flows in sawmills.

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