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FACTORS AFFECTING THE EFFECTIVE TIME CONSUMPTION, WOOD RECOVERY AND FEEDING SPEED WHEN MANUFACTURING LUMBER USING A FBO-02 CUT MOBILE BANDSAW

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ABSTRACT

In this study the efficiency of a FBO-02 CUT mobile sawmill is analyzed in terms of effective time consumption for sawing, recovery rate and feeding speed for five wood species. Following a work measurement study, we found that, in given conditions, a wood recovery as high as 66 % may be obtained. Also, the wood recovery rate may be satisfactory expressed as a function of the log volume. The feeding speed was mostly affected by the moisture content, lumber thickness and lumber width while the effective time consumption for sawing one log was mostly affected by number of cuts, log length and log volume. On the other hand, wood species, lumber length and lumber width were the most significant independent variables when trying to explain the effective time consumption for sawing each lumber piece. The presented results may be helpful in various applications such as operational planning and costing, technology and work methods improvement.

KEYWORDS: Sawing, lumber, efficiency, recovery rate, effective time consumption, FDO-02 CUT.

INTRODUCTION

Wood harvesting as well as its subsequent industrial processing represent ones of the main economic activities contributing to the Romanian Gross Domestic Product (GDP). These industries as well as other related upstream and downstream economic processes offer employment for many people, especially in the rural areas of Romania. Currently, the Romanian forests cover about 27 % of the national territory being almost equally distributed between the state and private ownership, while the national yearly allowable cut was estimated in 2010 to be around 22 mil. m^3 (Report on forest state 2010). While in Romania the timber harvesting as a production process is mainly performed in order to supply the downstream related industries (Oprea 2008), a survey done by Sbera (2007) revealed that in the overall Romanian wood industry, the timber harvesting and primary processing related industries had a share of almost 32 %. According to the same source, a total quantity of 4.470 mil. m^3 of lumber was produced by about 7000 manufacturing facilities, most of them having a capacity of 8-10 m^3 per day. In Romania, experience shows that wood sawing facilities are located in most of cases outside the forests, but motor-manual sawing activities may be performed also in the felling areas followed by lumber hauling, as reported by Jourgholami et al. (2010).

Band sawmills are known as one of the technological alternatives used for lumber production, while their use in a full processing of a log supposes several cutting and manipulating phases (De Lasaux et al. 2009). In small scale sawing applications, such equipments offer an improved wood recovery rate by comparison with free-hand motor-manual sawing (Cedamon et al. 2013), while in more or less industrial applications the efficiency of such equipments is mostly affected by the volume of logs to be processed (Ištvanić et al. 2009). On the other hand, the recovery rate of green-off-saw (GOS) timber from logs and the speed at which the logs can be converted into lumber have a major impact over the costs of operating sawmills (Venn et al. 2004).

For a given sawmill, the GOS recovery rate is frequently assessed based on the total wood input into sawing process, and the resulted quantity of sawn wood. In the same time, the efficiency of such equipments, in terms of time consumption and productivity, is often assessed using time studies (De Lasaux et al. 2009, Ištvanić et al. 2009). Such studies are used in order to develop empirical models for new, unstudied equipments, or for equipment used in new conditions (Visser and Spinelli 2012). In general, when using these scientific methods, one may perform either a modeling or a comparative study (Magagnotti and Spinelli 2012). The first type of studies may help in expressing some inputs or outputs as a function of one or more process variables, a case in which the used statistical procedures, as well as the resulted empirical models should consider the mechanical characteristics of the process or equipment under study (Magagnotti and Spinelli 2012).

The studies done so far addressed specific sawmilling equipment and working conditions, including the work pattern. Thulasidas and Bhat (2008) conducted a study on sawmilling teak timber harvested from different locations and they found out that the recovery rates ranged between 66.8 and 78.8 %. Ištvanić et al. (2009) conducted a study on a 75 kW log band saw and they found out that the capacity of such equipment is influenced in a great measure by the volume of the processed logs. Following a detailed time study, the authors established empirical relations between the feeding speed respectively the log band saw capacity and certain independent variables such as the diameter at the middle of the log, log length and the volume of the log. The same authors found out that the effective sawmilling time may account for a share as high as 46 % of the total operational time. About the same time, De Lasaux et al. (2009) studied a mobile small-log sawmill system – Economizer – and found out that productivities of 0.3 – 2.8 $m^3 \times h^{-1}$ may be obtained when processing boards and cants, while the recovery rate for the same products ranged between 50 and 67 %. They also found out that the sawing time was strongly affected by the log volume and length, and they expressed the recovery rate as a function of various independent variables such as the processed product, log taper, log length, lumber thickness and combinations between the mentioned. More recently, Cedamon et al. (2013) conducted a comparative study on sawmilling process and they found out that significant differences may occur in what concerns the recovery rate when using different kind of equipment. They reported that the recovery rate was much smaller when using on-site motor-manual sawing if compared with the use of a fixed-site mini-bandsaw mill. They also developed empirical models in order to estimate the recovery rate as a function of the log diameter.

By analyzing the existent reports, it is obvious that many factors may affect the efficiency in use when sawmilling timber. One of the key factors in efficiency studies is the used equipment as there are many available small-scale or industrial technologies for sawmilling.

In this context, our study aimed to test the efficiency of a Romanian made FBO-02 CUT mobile band-saw mill when manufacturing lumber from five species. The objectives of this study were to: (i) Identify the significant factors which affect the effective cutting time of the bandsaw, (ii) estimate the recovery rate for the five species and develop prediction models serving this purpose, and (iii) to identify if there are significant differences in the cutting time and feeding speed induced by log species.

MATERIAL AND METHODS

Description of tested bandsaw and work pattern

The FBO-02 CUT (Fig. 1) is a Romanian made mobile bandsaw which may be used for sawing different wood species, and which was designed for sawing logs having a maximum diameter of up to 95 cm. Logs are feed to the sawing band using a specialized carriage which serves to their holding during sawing. The basic technical description of the studied equipment is given in Tab. 1. When manufacturing lumber, the sawing operations consist of several phases repeated on a cyclic basis (Fig. 2), such as: Positioning of a log on the carriage, choosing the direction of the first cut, performing of the first active feed followed by a retour. After the removal of two opposite slabs, sawing is performed on the required (marked) positions. This kind of equipment is usually operated by two workers.

Fig. 1: Romanian made FBO-02 CUT sawmill in operation.

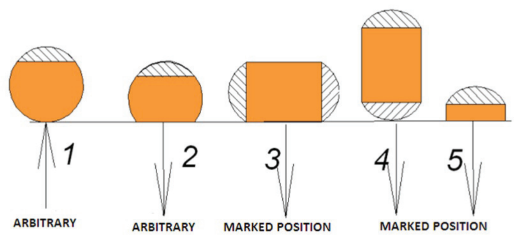

Fig. 2: Operational sequence of lumber manufacturing in this study.

Tab. 1: Technical description of FBO-02 CUT mobile band-saw.

Technical characteristic	Measurement unit	Value
Carriage engine		
Nominal power at 2940 rotations per minute	kW	7.5
Frame type	-	I32
Electrical installation		
Starter engine 380 with IP 55 frame	-	-
Electro-magnetic trigger		

Coil 02-462		
Thermal relay 02-483		
Dimensions		
Length		
- platform	mm	3 x 3000
- carriage	mm	1500
Width		
- platform	mm	1250
- carriage	mm	2250
Height		
- platform	mm	100
- carriage	mm	1650
Weight		
- platform	kg	145
- carriage	kg	235
Cutting band		
- thickness	mm	0.9
- width	mm	40
- length	mm	4650
- pitch	mm	22

During our study, a total number of 293 effective cutting repetitions were observed on a number of 30 logs selected from five representative species of Romania (Şofletea and Curtu 2008): oak (*Quercus robur* L.), beech (*Fagus sylvatica* L.), common alder (*Alnus glutinosa* L.), Norway spruce (*Picea abies* Lam. (Link.) and Silver fir (*Abies alba* Mill.). The logs were processed in lumber having mostly a thickness of 25 and 50 mm (Tab. 2). Only nine lumber pieces resulted at a thickness of 30 mm.

Tab. 2: Number of logs and the thickness of resulted lumber.

Wood species	No. of processed logs	No. of manufactured lumber pieces on thickness classes		
		0.025 m	0.030 m	0.050 m
Oak	6	5	0	34
Beech	6	0	5	34
Common alder	6	51	0	11
Spruce	6	75	0	6
Silver fir	6	52	4	13
Overall	30	193	9	98

Data collection

During the sawmilling operations we have collected values for several inputs, outputs and process variables. Time input was measured by adapting a time study the forestry concepts described by Björheden et al. (1995) respectively Magagnotti and Spinelli (2012). Time consumption was measured in seconds using a professional stopwatch for each sawing repetition (*Tlc*) by applying the snapback chronometry method (Björheden et al. 1995). The consumed time (in seconds) for effectively sawmilling each log into lumber (*TLc*) was obtained as a sum of times recorded for each cutting repetition. For each processed log, species (*S*) was visually assessed before processing. The diameter at the middle of the log (*DM*) and the log length (*LL*) were measured also before processing using a measuring tape and a forest caliper. Each lumber piece as resulted from processing was measured in order to determine its width (*LW*) and its thickness (*LT*), while its length was considered to be equal with the log length from which it was processed. We performed also a moisture content measurement for each processed log. For this purpose, we used a Moistec electronic moisture meter in order to collect sample data from three independent locations on each log. The final moisture content (*MC*) was calculated as the arithmetic mean of the three measurements. This value was multiplied by a scaling factor of 0.95 as provisioned by the moisture meter user guide. The number of performed cuts on each log (*NC*) was recorded in a field book designed for data collection. In the same field book we collected all the above described data.

Data analysis

In order to analyze the collected data, we have prepared a MS Excel sheet to suit the needs of this study. Some of the field collected data was transposed in the mentioned MS Excel sheet, while some of the data such as the log volume (*LV*), the effective time consumption for sawmilling one log (*TLc*), the volume of resulted lumber and the recovery rates (*RR*) were calculated based on the field collected data. Based on the values contained in the final database, we have developed time prediction models for each effective sawing as well as for the time effectively consumed in sawing lumber from each log. For this purpose we used the backward stepwise regression technique after performing a multicolinearity test for independent variables. We used for this purpose the Roemer-Orphal scale and an exclusion threshold for strongly correlated variables set at $R = 0.60$. While it is not given by any natural law (Magagnotti and Spinelli 2012), at each iteration, we used exclusion thresholds for the independent variables set at $p = 0.01$, value which expresses the accepted risk we acknowledged that one selected predictor was not significant for the developed model. The same value was used as a threshold in evaluating the global significance of the developed models. In order to include the species as a predictor in the model, we used a so-called "dummy variable" following the procedures explained by Zar (1974). The main advantage of this kind of variables is that they offer the possibility to make comparisons between treatments even in case of modeling studies and they are appreciated in forest and wood related time studies (Magagnotti and Spinelli 2012). The same statistical procedures were used in order to develop a predictive model for the recovery rate, as well as to estimate the feeding speed (*FS*) as a function of process variables. In order to do that, the recovery rate (*RR*) was calculated for each log apart, as well as for each species and for the overall experiment. For this purpose, we compared the volume of lumber products obtained from each individual log with its original value. A feeding speed (*FS*) model was developed using data derived from the time study and values collected for the process variables.

RESULTS

For the average conditions regarding the used work patterns, and the characteristics of logs (diameter at the middle of log of 42.03 cm, log length of 3.50 log volume of 0.456 m^3 and a moisture content of 44 %), our study yielded an average recovery rate of almost 66 %. However, the smallest values of this parameter were recorded in the case of Norway spruce (60.15 %) and common alder (60.16 %). Also, the effective time spent for sawmilling a log averaged 468.30 seconds with a maximum of 676.17 seconds in case of Silver fir and a minimum of 304.17 seconds in case of beech. Detailed descriptive statistics of the study are given in Tab. 3.

Tab. 3: Descriptive statistics of the sawingmilling process – dimensions, quantity, moisture content, recovery rate and effective time consumption during sawing.

Observed characteristics	Values			
	Minimum	Maximum	Range	Mean±St.Dev.
Oak (*Q. robur*)				
Diameter at the middle of log (cm)	28.00	57.00	29.00	43.83±12.54
Number of cuts per log	4	9	5	6.50±2.07
Log length (m)	2.5	3.5	1.0	3.00±0.45
Log volume (m^3)	0.154	0.862	0.708	0.509±0.308
Residue (m^3)	0.043	0.247	0.204	0.145±0.095
Recovery rate (%)	67.71	78.61	10.29	72.46±25.51
Moisture content (%)	21.21	31.50	10.29	25.51±3.51
Effective time consumption per log (s)	122.00	563.00	441.00	314.50±168.51
Beech (*F. sylvatica*)				
Diameter at the middle of log (cm)	27.00	62.00	35.00	44.33±12.93
Number of cuts per log	4	9	5	6.50±2.17
Log length (m)	3.0	3.00	0.00	3.00±0.00
Log volume (m^3)	0.212	0.833	0.621	0.453±0.256
Residue (m^3)	0.080	0.216	0.136	0.139±0.052
Recovery rate (%)	62.26	74.07	11.81	66.81±5.56
Moisture content (%)	58.71	65.89	7.18	62.35±2.78
Effective time consumption per log (s)	178.00	486.00	308.00	304.17±128.77
Common alder (*A. glutinosa*)				
Diameter at the middle of log (cm)	30.00	42.00	12.00	36.50±4.89
Number of cuts per log	7	13	6	10.50±2.74
Log length (m)	2.00	4.00	2.00	2.83±0.75
Log volume (m^3)	0.118	0.385	0.267	0.257±0.108
Residue (m^3)	0.054	0.144	0.090	0.100±0.037
Recovery rate (%)	54.24	63.24	9.00	60.16±3.22
Moisture content (%)	33.30	51.00	17.70	42.10±7.45
Effective time consumption per log (s)	190.00	520.00	330.00	378.67±151.09
Spruce (*P. abies*)				
Diameter at the middle of log (cm)	35.00	46.00	11.00	41.00±4.10
Number of cuts per log	11	16	5	13.83±1.83
Log length (m)	4.00	5.00	1.00	4.17±0.41
Log volume (m^3)	0.301	0.542	0.241	0.446±0.095
Residue (m^3)	0.129	0.216	0.087	0.177±0.035
Recovery rate (%)	57.14	64.68	7.54	60.15±3.25
Moisture content (%)	40.70	56.52	15.82	47.47±5.80
Effective time consumption per log (s)	439.00	880.00	441.00	668.00±163.64
Silver fir (*A. alba*)				
Diameter at the middle of log (cm)	38.00	55.00	17.00	44.50±7.18
Number of cuts per log	8	14.00	6	11.50±2.43
Log length (m)	4.00	6	2.00	4.50±0.84
Log volume (m^3)	0.418	0.865	0.447	0.614±0.198
Residue (m^3)	0.157	0.224	0.067	0.185±0.029
Recovery rate (%)	59.33	79.15	19.82	67.92±8.19
Moisture content (%)	34.20	57.50	23.30	42.60±9.05

Effective time consumption per log (s)	528.00	836.00	308.00	676.17±123.33
Overall				
Diameter at the middle of log (cm)	27.00	62.00	35.00	42.03±9.02
Number of cuts per log	4	16	12	9.77±3.61
Log length (m)	2.00	6.00	4.00	3.50±0.88
Log volume (m^3)	0.118	0.865	0.747	0.456±0.228
Residue (m^3)	0.043	0.247	0.204	0.149±0.060
Recovery rate (%)	54.24	79.15	24.92	65.50±6.80
Moisture content (%)	21.21	65.89	44.68	44.01±13.30
Effective time consumption per log (s)	122.00	880.00	758.00	468.30±219.66

Considered as predictors, the variation of moisture content, as well as the wood species, did not affect the variation of the wood recovery rate in this study, as the full regression analysis revealed. However, the volume of log (*LV*) seemed to explain to a greater extent at a chosen confidence threshold ($p<0.01$) the wood recovery rate. An overview of the recovery rate as a function of the log volume is given in Eq. 1.

$$RR = 16.369 \times LV\,(m^3) + 58.039 \qquad N=30,\ R^2 = 0.30 \qquad (\%) \qquad (1)$$

On the other hand, our study results show that the lumber thickness (*LT*), lumber width (*LW*) and the moisture content (*MC*) were the most relevant predictors when trying to explain the variation of feeding speed (*FS*). The empirical relation between the mentioned predictors and the feeding speed is presented in Eq. 2. It should be mentioned here that a certain the feeding speed was maintained by the mill operator. Therefore, it is expected that the feeding speed to be related also to the operator's work behavior and experience. In average, each piece of lumber milled from oak logs was processed at a feeding speed of 0.068 $m\times s^{-1}$ which was not so far away by that recorded in the case of beech lumber (0.066 $m\times s^{-1}$). In the case of common alder and spruce, average feeding speeds of 0.082 and 0.088 $m\times s^{-1}$ respectively were recorded while in the case of fir, the feeding speed was of 0.077 $m\times s^{-1}$. However, when it came about the elaboration of a feeding speed model (Eq. 2), the wood species (S) failed closely to be significant at the chosen confidence threshold (p = 0.09).

$$FS = 0.1115 - 0.0002 \times MC\,(\%) - 0.228 \times LT\,(m) - 0.078 \times LW\,(m) \qquad (m.s^{-1}) \qquad (2)$$

As shown in Tab. 4, the time consumption for the effective processing of one log (TLc) was most affected by the number of cuts per one log (NC), log length (LL) and log volume (LV).

All the mentioned independent variables were significant at the chosen confidence level ($p<0.01$). Also, the determination coefficient for the mentioned model (R^2=0.94) may be interpreted as the proportion of the time variation explained by the model's predictors. At the level of each single cut, the time consumption (*Tlc*) was best explained by the dummy wood species (*S*), lumber length (*LL*) and the lumber width (*LW*) as shown in Tab. 4. Here, the determination coefficient indicates that the variation of time consumption may be explained in a proportion of 71 % by the variation of model's predictors.

Tab. 4: Empirical time consumption models for individual cut and log levels.

Empirical time consumption model	Values					
	R^2	N	F	Sig. F	Predictor	P value
$TLc\ (s) = 36.091 \times NC + 93.528 \times LL\ (m) + 217.550 \times LV\ (m^3) - 310.70$	0.95	30	161.88	<0.00000	*NC*	<0.00000
					LL	<0.00000
					LV	<0.00000
$Tlc\ (s) = 2.689 \times S^* + 8.992 \times LL\ (m) + 79.173 \times LW\ (m) - 9.97$	0.71	293	233.71	<0.00000	*S*	<0.00000
					LL	<0.00000
					LW	<0.00000

* Species: S=0 for oak, S=1 for beech, S=2 for common alder, S=3 for Norway spruce, S=4 for Silver fir.

DISCUSSION

An increased recovery rate when processing lumber is a key aspect when dealing with an efficient utilization of wood. Some studies tried to explain the recovery rate as a function of diameter at the middle of logs (Cedamon et al. 2013) or as a function of log length, log taper and other combinations including the resulted wood product (De Lasaux et al. 2009). While there are many factors affecting the recovery rate, following the procedures of multicolinearity testing, we excluded from our study variables such as the log length and the diameter at the middle of log due to a potential artificial increment of the determination coefficient (Zar 1974), which may be the result of the existence of more or less deterministic, even if random, relations between predictors. This fact would be true in the case of volume since it was calculated as a function of the log's diameter and length. Therefore, we have kept only the log volume as an independent variable, a fact which seems to be more appropriate since the recovery rate is calculated based as ratio between the volume of obtained products and the initial volume of logs. On the other hand, wood species included in this study as a dummy variable failed to become a significant predictor when trying to explain the recovery rate during lumber manufacturing. Maybe this fact may be explained only by the work pattern chosen by the mill's operator, since no significant curvatures, taper or other wood defects related to wood species were recorded during the study. In what concerns the recovery rates reported by other studies, we found out that our study yielded results which are quite similar with those reported by De Lasaux et al. (2009) which found out that the recovery rate when producing cants may be as high as 67 %. Also, our results are comparable with those reported by Thulasidas and Bhat (2009). However, it should be mentioned that our results which indicate a mean recovery rate of about 66 % took into consideration the volume of log including bark as reference for calculation.

Previous studies indicate that the sawing time is affected by the log's volume and length (De Lasaux et al. 2009). Additionally, some studies considered also the diameter of log as explaining variable for time consumption (Ištvanić et al. 2009). Our study's results indicate that the time needed for the effective sawing of a log depends in a great measure by number of cuts, log length and the log volume, as this combination of predictors (very significant at $p<0.01$), explains the variation on the effective time consumption in a proportion of 95 % (R^2 = 0.95). In this study, at the log level, wood species and moisture content were not relevant at the chosen confidence level. This may be the result of masking effects generated by other factors not quantified in this study. While there are also other work elements which influence the overall time consumption, the effective sawing time may account for a share as high as 46 % (Ištvanić et al. 2009) of the total operational time, and developing an accurate time consumption model may help in organizing the production process. Apart of the model developed at the log level, we tried to estimate the time consumption for each cut as a function of certain predictors. Here, the maximal model included the moisture content, wood species, and the size of processed lumber (thickness, width, length and volume). Following a multicolinearity test, we have excluded the lumber volume and thickness as they were strongly correlated each other as well as with other variables. The remaining predictors were found to be very significant at the chosen confidence level, while their combination explained the variation of time consumption in a proportion of 71 %.

Ištvanić et al. (2009) showed the dependence between the log feeding speed and the diameter at the middle of the log for a stationary band-saw. They found out that the feeding speed decreases as the log's diameter increases and reported a mean feeding speed of 15.40 $m \times min^{-1}$ which was affected by the operator's behavior. In this study we conducted a feeding speed analysis at each cut level and we found out that the speed was affected by the moisture content, lumber thickness and lumber width. However, we acknowledge that the operator's behavior may influence the feeding speed in several ways. For example, as the diameter of the log increases, the width of the lumber will increase and the operator will tend to reduce the feeding speed. The same may be true when sawing ticker boards. Our study yielded a mean feeding speed of 0.079 $m \times s^{-1}$ (4.74 $m \times min^{-1}$), resulting in a much lower feeding speed if compared with the results reported by Ištvanić et al. (2009). However, this may be correlated with a more reduced nominal power of the bandsaw taken into study in this paper.

CONCLUSIONS

In this study we found out that the significant factors which affect the time consumption at the log and lumber piece level are the number of individual cuts, log length, log volume, respectively the wood species, lumber length and the lumber width. On the other hand, the variation of feeding speed used when sawmilling each lumber piece was affected by the variation of moisture content, lumber thickness and the lumber width. In what concerns this parameter, our study yielded a mean value of 0.079 $m \times s^{-1}$. Recovery rate varied as a function of the wood species, and according to this study it yielded a mean value of about 66 %. While we acknowledge that the recovery rate of lumber may be affected by various factors, of which some may be difficult to quantify, in this study we developed a prediction model as a function of only the log volume as it resulted after the use of multicolinearity testing and the backward stepwise regression techniques.

Since the available results are quite few in what concerns the sawmilling efficiency, and, in our knowledge, no results are available for the processing equipment we studied, the results presented by this study may be helpful for operational planning and costing of sawmilling activities when using small scale mobile equipment. Even if this study has rather an observational character, emphasizing the effect that certain factors may have over the sawing process inputs and outputs, its results may help for a better understanding of factors affecting the sawmilling processes in terms of time consumption, recovery rate and feeding speed.

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