

YARDING PRE-BUNCHED STEMS IN THINNING OPERATIONS: ESTIMATES ON TIME CONSUMPTION

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Abstract: *Harvesting operations in steep terrain are particularly challenging, especially in environmentally sensitive areas and in very dense forests that are prone to more damage when using mechanized equipment. A possible approach to limit the damage is that of integrating animal and mechanical equipment. A study was carried out to see what operational variables and to what extent are they affecting the time consumption of yarding pre-bunched stems in thinning operations applied to coniferous stands. Following a time and motion study of yarding operations it was found that the extraction distance and lateral yarding distance affected the variation of yarding cycle time. Within a work cycle, load attachment and detachment accounted for almost 65%, the rest being shared by other typical cable yarding functions. The statistics and models presented in this study may be of help in production planning, research and optimization.*

Key words: *pre-bunching, animal logging, cable yarding, steep terrain, time.*

1. Introduction

Romanian forests are spread across 27% of the national territory [10] being distributed, in their majority, in alpine steep terrains. Natural spruce (*Picea abies* Lam. (Link.)) forests cover roughly 22% (1.43 million hectares) of the forested area, predominating in the alpine landscapes [30] while those forests reaching their maturity and fulfilling production functions are managed under the clear-cut

silvicultural system and are commonly regenerated artificially by plantation. However, in the Romanian forest management, the clear-cuts are limited to areas no larger than 3 hectares [19] and prior to the clear-cuts, thinning operations are carried on up to an age of three quarters of the harvesting age. Also, the removal intensities in the Romanian thinning operations are usually in range of 5-18% [19].

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By its size, timber coming from thinning operations, and especially that form the first ones has fewer utilizations in the industry, while the harvesting operations themselves may be characterized by low productivities [21] due to reduced size of the harvested trees. In addition, harvesting in steep terrain is particularly challenging because the work is both difficult and hazardous. In such terrains, slope itself burdens the workers [27] by the need to frequently walk up and down the slope.

When the manual cable work is deployed on very long distances, the time consumption and productivity are affected [8] while the workload can increase as an effect of slope, distance and cable weight. Such effects were addressed by studies focused on forest operations ergonomics that aimed to reduce the workload experienced by workers in steep terrain [23] and [28]. One way to reduce the workload is that of limiting the distances that operators need to deploy cable work. This could be achieved by integration of equipment, specifically in steep terrain and dense stands where the cable work can generate increased damage to residual trees. Such extraction systems could integrate animal-powered skidding.

There is a general consensus that animal logging is characterized by rather low productivities. Nevertheless, it is used in many regions due to various reasons such as the lack of technology and the need to carry on operations in very dense stands where other equipment could generate increased damage on residual trees. To manage its low productivity, extractions with such equipment should be limited to less than 100 m [21] or it should be combined by integration with other kind of mechanized equipment where the animal logging should be used to pre-bunch stems [21]. Both concepts (integration and pre-bunching) referring to the animal logging are not new as they were described in the

available literature [21] and [22] as a measure to manage various harvesting conditions. Nevertheless, few studies reported on the performance outputs of such equipment integration. An example is that of [17], who studied the performance of integrating animal skidding with crawler tractors in environmentally-sensitive areas. They found that such equipment integration results in cheaper operations enabling a sustainable use of animal powered logging.

This is important as the use of draught horses supports the jobs in rural areas while their use could be seen as declining lately. For instance, [18] found that only 26% of the Hungarian forest districts use horse logging and only 2.6% of them own such equipment, while the willingness or ability to work with such equipment is rather low. The integration of animal and mechanized equipment worth exploring as the negative effect of increased time consumption [2] and low productivity [5] and [24] of animal logging could be effectively managed by the use of mechanized equipment to further extract the wood on long distances, improving this way the system's productivity and cost balance while minimizing the soil impact [21].

At the same time, cable yarding is the backbone of steep terrain harvesting operations being used in many regions across the globe [4] but the use of such equipment still remains expensive [26], especially for the Romanian context. Romania had a substantial experience in producing and using cable yarders, but similar to other countries [12] the use of such equipment is characterized by a decline [21] being gradually replaced by skidders. However, in alpine regions of Romania the use of skidders is usually associated with poor time management and rather low productivity [6] as well as with environmental impact due to the construction of bladed skid roads [9]. Conversely, the use of modern tower

yarders is still limited in Romania by the poor road access into forests [25], accepted harvesting methods [7], management prescriptions in low-extraction selective thinning operations and costs that are still high [26] even if the innovation of such equipment led to improves functionalities and capabilities [13] including fast installing and dismantle operations [29]. Nevertheless, the use of long-distance sledge yarders could cope with some of the limited access, but in thinning operations there is a question of cost control due to installing, operating and dismantling the yarders as an effect of low extractions per tree and per hectare, as being specific to Romania. Therefore, one option in steep terrain would that of integrating the animal-powered skidding with sledge yarder extraction [21] and [22].

The goal of this study was to evaluate and model the time consumption of yarding pre-bunched stems in coniferous thinning operations.

The study objectives were set to: (i) developing descriptive statistics of the time consumption work elements and relevant operational variables and (ii) modeling the time consumption of a cable yarding work cycle and individual work elements as functions of the operational variables taken into study.

2. Materials and Methods

2.1. Study Area, Work Organization and Equipment Description

Data used in this study was collected from a field study that was carried out in 2017, in a Norway spruce (*Picea abies* Lam. (Link.)) stand located in compartment 120A that was partially harvested being located at approximately 45° 15' 27'' N 25° 17' 50'' E, 1450 m above the sea level, Dâmbovița county, Romania.

Forests in the area are mixed and dominated by beech (*Fagus sylvatica* (L.)) being managed by the State Forest District of Pucioasa. A description of the site and harvesting conditions is given in Table 1.

Tree-length harvesting method was implemented to extract the wood originating from thinning operations.

The used harvesting system consisted of motor-manual tree felling, debranching and topping followed by the delivery of more or less pre-bunched stems, using animal powered skidding, near a cable yarding corridor. From there, the stems were yarded to the road side using a sledge yarder installed into a gravitational setup (Fig. 1).

Description of the study area

Table 1

Parameter	Value
Forest management data	
Area [ha]	16.10
Mean slope [°]	33
Species	100% Norway spruce
Harvesting data	
Mean age [years]	69
Average DBH [cm]	22
Average height [m]	19
Number of harvestable trees	8062
Harvestable volume - forest management estimations [m ³ o.b.]	2084
Average tree volume [m ³ o.b. × tree ⁻¹]	0.258
Silvicultural system	Thinning
Harvesting method	Tree-length



Fig. 1. A typical snapshot of yarding pre-bunched stems

The yarder used was a standard Wyssen W30 equipped with a 4-ton radio-controlled clamping HY4 carriage mounted on a 26-mm skyline and pulled by a 11-mm mainline. The yarder was setup in a downhill gravitational configuration, with the sledge placed uphill.

Cable yarding operations were carried out by a sledge operator, a poleman (worker responsible by the task at the roadside) and 1-2 choker setters. Prior the study, the verbal consent to participate was obtained from both, the company management and the workers to be observed.

The workers had a fair experience in cable yarding operations and the authors are convinced that they could be also seen as being representative for the gravitational downhill yarding operations implemented in Romania.

2.2. Experimental Design, Data Collection and Analysis

The experimental design of this study was shaped around a traditional observational modelling study [1] meaning

that the variation of yarding cycle time consumption (CTY_{15} , seconds) - as the sum of time consumption of the component work elements - was assumed to be dependent on the variation of operational variables such as the extraction distance (ed), lateral yarding distance (ld) and slope on the direction of lateral yarding (s). The same assumptions were made for some of the observed work elements and some of the operational variables. In particular, there were assumed dependence relations between the time consumption during the carriage-in work element (t_{ci}), carriage-out work element (t_{co}), and the extraction distance (ed), respectively between the time consumption during the cable pull-out work element (t_{cpo}), cable pull-in and load lift work element (t_{cpil}), and the lateral yarding distance (ld) and slope on the lateral yarding direction (s), respectively. These assumptions were made based on previous studies carried out for winching operations in steep terrain [8]. Following the same assumptions as well as the recommended practices when developing time consumption models [1] both, the variation of cycle time consumption and of

the elemental time consumptions for the mentioned work elements were assumed to be linearly dependent on the variation of operational variables.

Therefore, a yarding work cycle (WC_Y) was divided into work and time elements specific to the operations and equipment taken into study. For this, we used as a reference the cable yarding functions described by [13]. In particular, work and time elements such as the carriage-in ($we_{ci} - t_{ci}$), lowering the cable ($we_{lc} - t_{lc}$), cable pull-out ($we_{cpo} - t_{cpo}$), load attachment ($we_{la} - t_{la}$), cable pull-in and load lift ($we_{cpill} - t_{cpill}$), carriage-out ($we_{co} - t_{co}$), lowering the load ($we_{ll} - t_{ll}$), load detachment ($we_{ld} - t_{ld}$) and cable lift ($we_{cl} - t_{cl}$) were monitored in this study.

To this end, a pen-and-paper time and motion study was designed and implemented for a number of about 70 operational hours.

A professional stopwatch was used to get the time consumption data using the continuously timing method as defined by [3]. Given the methods and instruments used, it was not possible to account for and separate from the time consumption data short and repetitive delays. For this reason, we assumed the inclusion in the study of delays accounting for less than 15 minutes within an operational hour, as an accepted approach to deal with such situations in forest production studies [1]. No measurements were taken on the timber inputs as both, the number of stems per load and their dimensional variability were high and it was obvious that such measurements would affect the study by researcher induced delays. The extraction distance (ed) was measured prior the extraction operations, using a Nikon Forestry Pro laser rangefinder, in a step-by-step approach that included measurements followed by placement of painted markings on the corridor's nearby trees using biodegradable paint (Fig. 1).

Then, the extraction distance for each of the work cycles was estimated by addition or subtraction, during the operations, using the same instrument, based on the numbers written on the nearby trees and the position of the carriage relative to the closest mark. Lateral yarding distance and the slope on the lateral yarding direction were measured from beneath the carriage to the load to be attached within each work cycle. Measurements described above were undertaken for a number of 321 work cycles. Data gathered in the field was manually transferred into a Microsoft Excel worksheet where it was systematically organized on days and work cycles, following the calculations by difference of time consumption on work elements.

Statistical analysis consisted of several steps. Firstly, outliers were identified and excluded based on logical reasons for those observations showing obvious errors or inconsistencies, then a correlation analysis was implemented for independent variables with a correlation coefficient set at $R \leq 0.75$ as an acceptable threshold to exclude the independent variables from regression analysis for reasons such as the inflation of determination coefficients [31]. Following these steps, descriptive statistics of time consumption and of the operational variables were computed and a stepwise backward regression procedure was used to model the variability of yarding cycle time as a function of independent variables. Significance of the model and independent variables were tested and evaluated for a threshold set at $\alpha = 0.05$ using the p -values ($p \leq 0.05$). A similar approach was used to develop time consumption models for the selected elemental time consumption elements and the operational variables with the difference in the type of the regression technique used (simple linear regression). The estimative capacity of the developed

models was appreciated using the adjusted coefficient of determination (R^2 statistic). All of the needed computations and statistical analyses were carried on using the Microsoft Excel software.

3. Results

3.1. Descriptive Statistics of Time Consumption and Operational Variables

Data used in this study was collected by observing in the field a number of 321 work cycles. However, some data refinement was necessary to exclude those data observations showing obvious errors and inconsistencies, resulting in a final data pool to be analysed consisting of 316 work cycles. Table 2 shows the computed descriptive statistics of the time consumption and operational variables. Both, the lateral yarding distance and slope on the direction of lateral yarding were observed for a number of 269 work cycles

meaning that for a number of 47 observed work cycles the wood was extracted directly from beneath the skyline. For those cases in which the mainline was pulled out to attach the loads, the lateral yarding distance varied widely between 10 and 55 m, averaging about 25 m. The slope on the lateral yarding direction varied between 10 and 38°, averaging about 24°. The extraction distance averaged about 289 m and varied between 85 and 658 m.

In these operational conditions, a complete yarding cycle took, in average, about 795 seconds.

Speed of carriage-in work element averaged $5.2 \text{ m}\times\text{s}^{-1}$, while the speed of carriage-outworkelement averaged $4.3 \text{ m}\times\text{s}^{-1}$ showing an obvious difference that can be related to the loads touching the ground when extracted as well as to slowing down when passing the shoes. As a fact, the carriage-out work element took almost 2.5 more time than the carriage-in work element.

Descriptive statistics of operational variables, time and fuel inputs Table 2

Work (time) element	Descriptive statistics					
	N	Sum	Share [%]	Min.	Max.	Mean ± St. dev.
Operational variables						
Lateral yarding distance, ld [m]	269	-	-	10	55	24.9±10.
Lateral yarding slope, s [°]	269	-	-	10	38	24.2±6.5
Extraction distance, ed [m]	316	-	-	85	658	289.3±121.3
Time consumption variables						
Carriage in, t_{ci} [s]	316	17735	7.06	13	136	56.1±22.6
Lowering the cable, t_{lc} [s]	316	4160	1.66	2	30	13.2±3.2
Cable pull-out, t_{cpo} [s]	316	14314	5.70	0	169	45.3±32.1
Load attachment, t_{la} [s]	316	131000	52.15	55	936	414.6±137.2
Cable pull-in and load lift, t_{cpil} [s]	316	14948	5.95	9	428	47.3±45.1
Carriage out, t_{co} [s]	316	21911	8.72	16	338	69.3±34.4
Lowering the load, t_{ll} [s]	316	6520	2.60	4	190	20.6±21.2
Load detachment, t_{ld} [s]	316	31841	12.68	20	576	100.8±68.43
Cable lift, t_l [s]	316	8755	3.49	4	127	27.7±17.5
Yarding cycle time, CTY_{15} [s]	316	251184	100.00	372	1427	794.9±168.7

Notable in the work cycle time consumption structure was the load attachment which accounted for more than 50% and it was strongly related with the local work conditions characterized by a high number of stems per load and by an increased slope.

Next in line was load detachment at the roadside which accounted for almost 13% being related to similar reasons, including here the high number of stems per load and the wood agglomeration at the roadside.

The predictive model of cable yarding cycle time is given in Table 3. While both, the used predictors and the model itself were significant, the predictive capacity of the model could be interpreted as being rather low, judging by the adjusted coefficient of determination (adj. $R^2 = 0.22$). This could be the effect of

other work elements, included in the data pool that showed a high variability while they could not be related to any of the operational variables taken into study (e.g. load attachment).

Figures 2 and 3 show the dependence relation between the carriage-in, carriage-out and extraction distance. The latter's variability explained the variability of time consumption during the carriage-in work element in a proportion of 93% (adj. $R^2 = 0.93$). Obviously, such a good fitting was the effect of insignificant delays during this work element which ran smoothly in particular. Nevertheless, one can observe that the variability of the data pool increased as a function of extraction distance. Probably this is the effect of slowing down the carriage when crossing over the shoes in this work element.

Prediction of cable yarding cycle time

Table 3

Cycle time consumption model	Model statistics				
	N	adj. R^2	Sig. F	Variable	p value
$CTY_{15} [s] = 0.704 \times ed [m] + 2.407 \times ld [m] + 540.431$	316	0.22	<0.001	ed	<0.001
				ld	<0.001

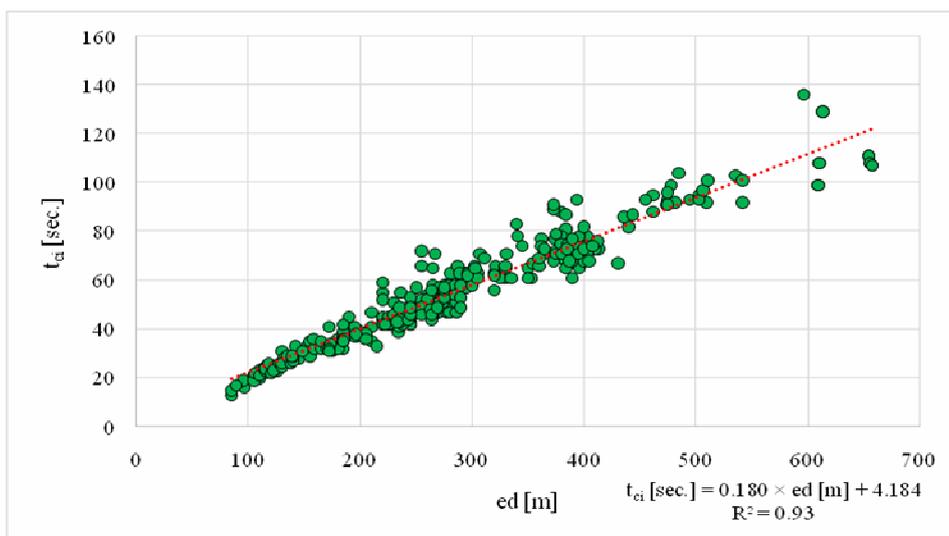


Fig. 2. *Variation of time consumption for carriage-in as a function of extraction distance*

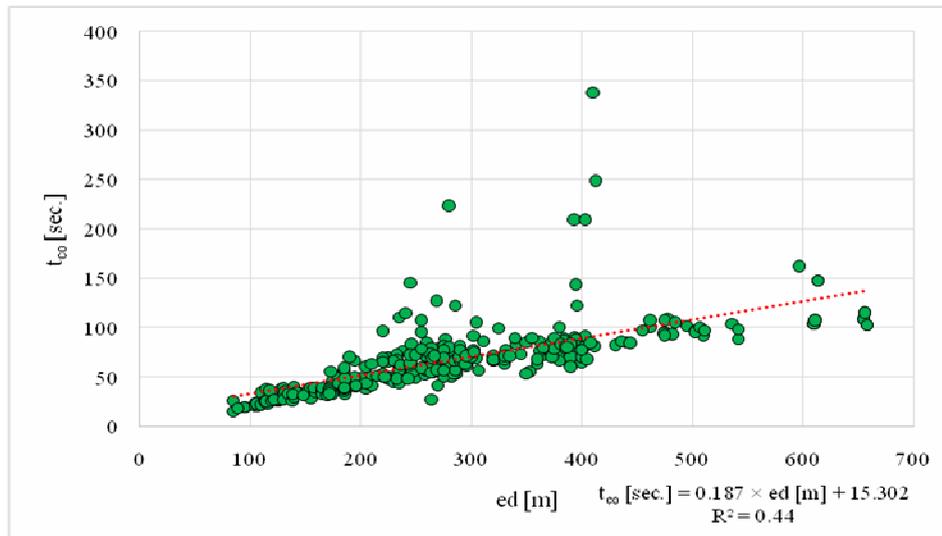


Fig. 3. Variation of time consumption for carriage-out as a function of extraction distance

The model of carriage-out work element as a function of extraction distance (Fig. 3) did not return a similar, good predictive capacity. However, it was close to the field reality in which the loads were extracted downhill with much care when crossing over the shoes. Then, the loads were not fully suspended and this caused also a part of the variability. Nevertheless, those observations indicating an excessive time consumption in this work element (Fig. 3) were not actually outliers but some of those observations that were classified as including delays less than 15 minutes within a working hour and which could not be treated separately given the methods used in data collection.

Table 4 shows the predictive model of time consumption as a function of lateral

yarding distance and slope on the lateral yarding direction for the cable pull-out work element.

Both of the used predictors were significant at the chosen confidence level, but the predictive capacity of the model was reduced ($R^2 = 0.29$). It should be mentioned here that the loads were predominantly laterally yarded uphill relative to the carriage location (216 out of 269 cases in which the cable pull-out occurred). Therefore, a model showing an increased prediction capacity was expected following the regression analysis but this assumption was not met, probably due to the variation of distance and the position of stems relative to the cable yarding corridor.

Prediction of cable yarding cycle time

Table 4

Cycle time consumption model	Model statistics				
	N	adj. R^2	Sig. F	Variable	p value
$t_{cpo} [s] = 1.450 \times ld [m] + 0.767 \times s [^\circ] - 1.425$	269	0.29	<0.001	ld	<0.001
			01	s	<0.001

Regression analysis of cable pull-in and load lift returned even worse results that are not presented herein. That was the effect of the high number of stems per load, frequent reattachments and stops during this work element, which could not be accounted separately.

4. Discussion

This study aimed to develop descriptive statistics and model the time consumption for yarding of pre-bunched stems in coniferous thinning operations. Such results are particularly helpful in managing the production, setting rates and cost control of harvesting operations [1]. In addition, the results may be of use when optimizing the harvesting systems by including also the road building and maintenance costs [11], [14] and [15], as part of a production cycle that should account also for tendering operations. In that direction, cable installation and dismantling time is important and should be considered. Such inputs were not accurately measured in this study but observed in the field. Cable installation and dismantle took 4 and 3 days respectively, with costs of about 330 and 220 euro respectively (for a gravitational downhill extraction setup of about 700 m). While not estimated in this study, the production in such operations was provided by the company management based on their accounting system and is was estimated at about 36 m³ over bark (o.b.) per day, with a diesel input of 22 l per day, probably resulting in about 0.6 l of diesel per extracted m³ o.b. Pre-bunching using animal powered equipment was paid based on production with about 4.4 euro per m³ o.b. while yarding was paid differently based on timber location during operations: about 2.2 euro per m³ o.b. for the pre-bunched stems and about 4.4 euro

per m³ o.b. for those stems resulting from corridor opening.

In what concerns the developed models and statistics, some points may be discussed. An average cycle time took in this study about 12 minutes for an extraction distance of about 290 m and a lateral yarding distance of about 25 m, results that are in the range reported by [16]. The same authors objectively argued the less usefulness of reporting time consumption models characterized by a low predictive capacity and we agree with that opinion. Nevertheless, we chose to report the cable yarding model even if it was characterized by a low predictive capacity based on the rationale that its predictive capacity could be affected by the high variability of other work elements as being specific to this study. For instance, load attachment varied widely between 55 and 936 seconds and it accounted for a share greater than 50% of this study. Obviously, such a condition would affect the variation explained by the measured operational variables by inclusion within the model. This could be seen also in the intercept of the developed model that could be interpreted as the portion of the time not explained by the operational factors as described in [20]. This becomes even obvious when analyzing the model enclosed in Figure 4 that returned a good predictive capacity as an effect of less delays that were missed by the timing methods and techniques used in this study. Obviously, this was not the case of the model included in Table 4 where the low predictive capacity could come from missing one or more important factors as independent variables. Still, the slope on the lateral yarding direction became significant in this case, probably due to the same reasons as mentioned above.

A limitation of this study is that of being observational in character, with the developed models and statistics being valid

only in the range covered by the used data pool. Nevertheless, is quite difficult to control given variables when conducting such studies in steep terrain and it is even more difficult to carry on studies in such conditions [1] while the results of the study may be used as a reference given the lack of statistics on such operations, at least in Romania.

In what concerns the observed harvesting system, research should be extended to see to what extent the animal-powered pre-bunching should be deployed relative to the operational distance to optimize the system's integration as such extraction systems could be a good fit for steep terrains and environmentally-sensitive areas. To this end, judging by the shape of the harvested area and the location of placed cable yarding corridors (not given in this study), the extraction distance by animal-powered equipment never exceeded 100 meters which is in line with the recommendations formulated by [21].

5. Conclusion

Similar to most of the cable yarding time studies, the cycle time variation in this study was affected by the extraction distance and by the lateral yarding distance. The developed models were characterized by quite different predictive capacities due to variation in factors that either were not measured in this study or could not be related to the time consumption of certain work elements. In conditions in which the load attachment and detachment accounted for almost 65% of the study time as an effect of the payload characteristics, the mean yarding cycle time was estimated at about 11.5 minutes for an average extraction distance of about 290 m, a lateral yarding distance of about 25 m and a mean slope on the lateral yarding direction of about 24°.

The results of this study may be of help in production planning, research and optimization.

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