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TOWER YARDER WORK TIME AND PRODUCTIVITY STUDY IN RHODOPE MOUNTAINS

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Abstract: *Ground-based vehicle logging systems require a dense network of skid roads as the terrain gets steeper. In terrains where the slope is 40% and greater, cable yarding systems are expected to be most efficient and environmentally-sound than ground vehicle systems. Nowadays small cable yarding systems are used mainly for uphill yarding. The main reason is that uphill yarding systems are much easier and faster to rig. The most common timber harvest unit layouts are parallel or fan-shaped [17]. In Bulgaria approximately 60% of the forests are situated in mountainous areas with steep slopes and complex terrain shapes. The logging sites in Rhodope Mountains, South-Central Bulgaria are between 400 and 1200 meters above sea level. Typically, in Rhodopes Mountains the sloppy and smooth terrain predominate, which give an opportunity to uphill yarding. In Rhodope Mountains forests consist mostly of Norway spruce (Picea abies L.) and Scots pine (Pinus sylvestris L.). The aim of the present study is to improve the use and operational efficiency of the tractor-mounted cable yarder in coniferous stands and to determine the time and volume of logs transported per unit of the yarder. Knowledge of these parameters is useful for defining the operational efficiency of cable logging and improvement of cable yarder performance. The main results indicate that the productive time for the studied cable yarder was about 87% and operational and mechanical delays accounted respectively for 5.5% and 7.5% of the scheduled machine hour. The mean yarding productivity, excluding and including delays, estimates at 38.82 m^3 per shift and 36.27 m^3 per shift, respectively, i.e. close to the maximum for that type of cable yarders under given condition.*

Key words: *cable yarder, work cycle time, yarding productivity, delays.*

1. Introduction

Ground-based logging systems require a dense network of skid roads as the terrain gets steeper. In terrains where the slope is 40% or greater, cable yarding systems are expected to be more efficient and environmentally-sound compared to ground based systems. Cable-based technologies have been a backbone for harvesting on steep slopes [1].

Cable yarding is taking logs from the stump area to a landing using an overhead system of winch-driven cables to which

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logs are attached with chokers [22]. Standing line is fixed cable that does not move during logging operations; for example, a skyline anchored at both ends. Mobile cable yarders have tower – steel mast used instead of a spar tree at the landing for cable yarding.

On steep terrain, cable yarding is the cost-effective alternative to building an extensive network of skidding trails and results in a much lower site impact compared to ground-based logging [19].

Yarding causes the least stand and soil damage, suggesting that silvicultural prescriptions should favour the application of cable logging, if possible [19]. Cable yarding also has the advantage of minimizing the impact in environmental sensitive areas and can be integrated into biodiversity goals and ecosystem management plans [6, 13]. In general, cable yarding is more complex and expensive than ground-based logging, which places the steep terrain cable yarding operations at a general disadvantage in terms of pure harvesting cost. However, modern cable yarding technology can fill this gap, and productivity models can assist users in refining their work technique, so as to maximize the productive potential of their machines [20].

Nowadays small cable yarding systems are used mainly for uphill yarding. The main reason is that uphill yarding systems are much easier and faster to rig. The most common timber harvest unit layouts are parallel or fan-shaped [17].

In Bulgaria approximately 60% of the forests are located in mountainous areas with steep slopes and complex terrain configurations. The logging sites in Rhodope Mountains, South-Central Bulgaria, are located between 400 and 1200 meters above sea level. Typically, in Rhodope Mountains the sloppy and smooth terrain predominate, which give an opportunity for uphill yarding, and the forests consist mostly of Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.). Tractor-mounted tower yarders have been widely used in Bulgaria since 1980 in primary timber transportation.

Lateral yarding consists of moving the logs (load) to a bunching point from where the load is partly or entirely lifted off the ground by the cable (mainline) and moved to the landing. Therefore, a yarder is a system of power-operated winches used to haul logs from a stump to a landing. Tractor-mounted tower cable yarders are driven by power take-off shafts (Table 1). Both single- and multi-span layouts are used for tower yarders. For single-span layouts, a crew of 2-, 3-, and 4-members can be used when using solely a yarder and a 3- and 4-member crew when using both a yarder and skidder [8-9].

According to Huyler and Ledoux (1997b) the yarding delays for operational, mechanical, and non-productive time accounted for approximately 35% of the total cycle time on steep slopes in the US Northeast. The authors also proposed that delays should be factored to separate the delay-free time to be able to give an estimate of the total cycle time. The average delay-free-cycle time was 5,72 minutes [6]. The relevant variables used in the time prediction equation were the yarding distance, lateral yarding distance, volume per turn and stem volume.

In conditions of Italian Alps, productivity ranged between 8.5 and 10 m^3h^{-1}, including all delays, but excluding set-up and dismantle time. Machine utilization was about 60%, which was consistent with previous studies [20].

According to Dimitrov (2012), to increase the productivity of tractor-mounted tower yarder operated in beech (*Fagus sylvatica* L.) stands located in Ograzhden Mountains in Southwest Bulgaria, operational times for lateral outhaul (28%), inhaul (21%), nonworking time covering spare and delays of workers (16%) and unhook (13%) should be minimized. He also estimated that the mean productivity of the studied yarder of 3.22 m^3h^{-1} for 33-m lateral yarding and 230-m outhaul could be defined as moderate. The results are comparable with those of studies carried out in coniferous stands of Northeast Turkey – 6.6 m^3h^{-1}, 5.5 m^3h^{-1} and 4.9 m^3h^{-1} respectively for inhaul distances of 100, 200 and 250 m [18].

Table 1

Technical data of studied Koller K300T cable yarder

Parameter	Value
Skyline capacity 500 m, ø14 mm swaged or 450 m, ø15 mm	44 kN (tension section)
Mainline 550 m, ø8,5 mm swaged or 450 m, ø9,5 mm	18 kN (average drum)
Guyline	3x30 m, ø16 mm / 2x10 m (extension)
Line speed	Up to 3.6 ms^{-1}
Tower height	7.2m
Tower height (with tower extension)	8.4 m
Operating range	on the left side of the yarder
Power station	PTO of the tractor (mechanically driven)
Engine power of the tractor: 49 HP (36 kW)	minimum 36 kW (49 hp)
Clutch	Hydraulically operated single dry disk on both drums
Brakes	
Skyline	manually actuated band brake
Mainline	hydraulically actuated band brake
Operation	Hydro-mechanical / electro-hydraulic single lever operation with dead-man´s control
Carriage	Koller SKA-1 /SKA 1-Z
Weight	
without lines	1550 kg
including lines (non-compressed/compressed)	2050/2250 kg

Production rates observed by Zimbalatti and Proto (2009) during fuel wood yarding operations in two Turkey oak (*Quercus cerris* L.) stands in Calabria, Italy, were lower – mean load volume of 0.75 and 0.54m^3, and productivity of 2.38 and

$3.21m^3h^{-1}$, respectively for coppice and high forest. According to Melemez et al. (2014) the extraction by skyline was determined to be the most efficient extraction method, but the slope of the terrain needs to be greater than 50% to use this method.

As most of tractor-mounted tower yarders in Bulgaria operate in Rhodope Mountains in coniferous forests, time and productivity studies are of great interest because the data obtained in such studies could be used to develop simulations in order to give loggers and forest managers an effective tool for operational planning in similar terrain conditions. Most operations will be economical when taking place in a high-yield stand and when all factors affecting costs of operations have been considered carefully [10].

The aim of the present study was to improve the use and operational efficiency of the tractor-mounted cable yarders in coniferous stands and to determining the time, and volume of logs transported per unit of the yarder. Knowledge of these parameters is useful to integrate the work of the cable yarders in order to achieve economic and environmental efficiency of timber extraction.

2. Material and Methods

The study focused on a Koller K300T tractor-mounted tower yarder~~s~~, which is among the most widespread in Bulgaria.

The work team consisted of three people, of which one was the winch operator and unhooks the logs, and the rest were choker-setters at the loading site. The work team had at least 5 years of experience with cable yarding and they were all 35-45 years old. The study was carried out in the Rhodope Mountains at the Kormisosh State Hunting Range and Borika Forest Owner Cooperative. Trees removed consisted of 100 years-old, Scots pine (*Pinus sylvestris* L.), with mean height of 26.0 m and mean diameter at breast height of 34 cm, and of Norway spruce (*Picea abies* L.), with mean height of 24.0 m and mean diameter at breast height 30 cm. To minimize residual stand damage~~s~~ during the lateral yarding the logs were extracted in lengths of 3, 4, 5 and 6 m. In most cases only one log was yarded.

Three skyline corridors were opened on terrain slopes of about 25° (47%), 30° (58%) and 35° (70%). Field observations were carried out on 30 work cycles (turns) at each corridor. Extraction direction was uphill. A double-span using double-tree intermediate supports (also known as M-support) layout was implemented each time. A detailed time and motion study was conducted to estimate the duration of work elements and productivity of the cable yarders in the given conditions. A yarding work cycle was assumed to be composed of repetitive elements [15-16, 20]. In this study the yarding work cycle was composed of following repetitive elements [16]: descending of empty hook, outhaul, lateral outhaul, hook, lateral inhaul, inhaul, unhook and delays.

The time-motion study was designed to evaluate duration of work elements and yarder productivity and to identify those variables that are most likely to affect it. Each yarding cycle was stop watched individually. Productive time was separated from delay time [11].

Yarding distances were measured with a laser range-finder, the terrain slope – with professional clinometer. Load volume was determined by measuring the length and the diameter at mid-length of all logs in each load.

Regression analysis was performed on the experimental data in order to develop prediction equations for estimating the work cycle time and productivity. Variables used in the modelling approach included lateral yarding distance *l*, yarding distance *L*, load volume per cycle *Q*, and terrain slope angle *s*.

Statistical analysis consisted of identification and exclusion of outliers, correlation analysis 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. The descriptive statistics of the variables were computed and a stepwise backward regression procedure was used to model the variability of yarding cycle time and productivity as a function of independent variables.

Since factors have different dimensions (m, m^3, degree), it is difficult to determine their impact. Factor coding is particularly effective and simplifies the computation of the regression model parameters [14, 24].

The confidence level used for regression analysis was $\alpha=0.05$ and the assumed probability $p<0.05$. Independent variables are significant at $p<0.05$, i.e. very strong presumption against neutral hypothesis.

To process the experimental data the Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software was used.

3. Results and Discussion

The summary of experimental data from 90 cycles for each of the selected variables used in the cycle time and production equations is shown in Table 2.

3.1. Duration of Work Cycle Elements

The greatest portion of cycle time (Figure 1) was specific to the inhaul (54% and 47% respectively, excluding and including delays) and it was most probably related to the low inhaul velocity of carriage with load; descending of empty hook accounted for the smallest share (1%). Hooking accounted for the second highest share (16% and 14% respectively, excluding and including delays). Operational and mechanical delays accounted respectively for 5.5% and 7.5% of the total cycle time of the studied cable yarder (Figure 1c).

The characteristics of independent variables in really values and code values are shown in Table 3.

The regression analysis was performed on the time-study data in order to develop a prediction equation for estimating the yarding cycle time by excluding and including delays. Significant variables were the lateral yarding distance *l* (m), yarding distance *L* (m), and terrain slope *s*, deg (Table 2). The delay-free cycle time T_{net} regression equation obtained with significant variables ($R^2=0.774$, $F(14.75)=18.311$, $p<0.05$) is as follows:

$$T_{net}=7.491+0.411x_1+1.065x_2+0.307x_4-0.809x_1x_2+0.727x_2^2-0.440x_4^2 \text{[min]} \quad (1)$$

In Eq. (1) minimum values of delay-free cycle time T_{net} may attain in case of low level of lateral yarding distance *l* (i.e. x_1=-1), and slope yarding distance *L* (i.e. x_2=-1), but high level of terrain slope angle *s* (i.e. x_4=+1). The variable load volume per cycle *Q* with code value x_3 is insignificant, probably due to the load consists mainly from one log.

The following regression equation for cycle time including delays *T* under the given forest conditions one obtained:

$$T=4.099+7{,}505x_2-2.893x_4-2.554x_1.x_4+12.290x_2x_3-4.668x_3x_4+3.767x_1^2+4.824x_3^2 \text{ [min]} \quad (2)$$

Regression summary of Eq. (2): $R^2=0.54$, $F(14,75)=6.29$, $p<0.05$, Std. Error of estimate: 4.174.

Consequently, the minimum duration of cycle time including delays achieves when $x_1=-1$, $x_2=-1$, $x_3=1$, and $x_4=1$, and respective natural symbols and values of factors.

Table 2

Mean experimental data

Yarding variables	Cycle time [min]			Distance [m]		
	Mean value ± St. dev	min	max	Mean value ± St. dev	min	max
Descending of empty hook	0.12±0.02	0.08	0.15			
Outhaul	0.58±0.06	0.42	0.67	202±35.36	180	230
Lateral outhaul	0.37±0.09	0.20	0.54	17.5±4.50		
Hook	1.38±0.35	0.90	2.13			
Lateral inhaul	0.80±0.12	0.56	1.08	17.5±4.50	10	25
Inhaul	4.56±0.60	3.26	5.36	202±35.36	180	230
Unhook	0.64±0.15	0.26	0.90			
Delay	1.30±5.72	0	30.00			
Total cycle time	9.82±5.99	6.40	38.74			
Delay-free cycle time	8.32±0.94	6.40	9.63			
Load volume per cycle (turn), m^3	0.66±0.21	0.37	1.23			
Productivity, m^3/PMH*	5.08±1.69	2.68	10.41			
Productivity, m^3/SMH*	4.73±1.73	1.47	8.59			
Number of cycles per SMH*	6.27	5.42	8.16			

*St. dev. – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour.

Table 3

Characteristics of independent variables

Characteristics	Really values				Code values			
	l [m]	*L* [m]	*Q* [m^3]	*s* [deg]	x_1	x_2	x_3	x_4
Low level	10	145	0.37	25	-1	-1	-1	-1
High level	25	230	1.23	35	+1	+1	+1	+1
Basic level	17.5	187.5	0.8	30	0	0	0	0

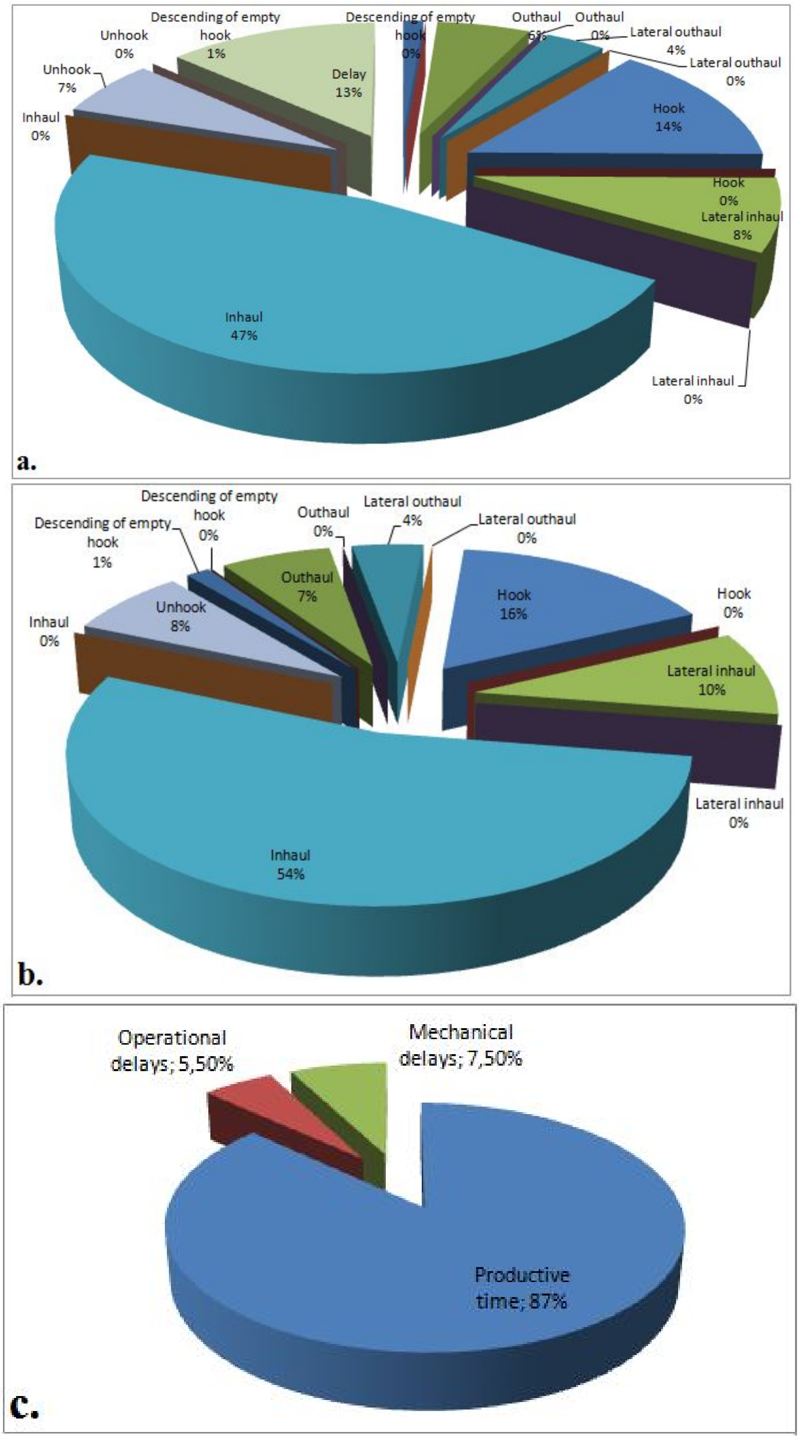

Fig. 1. Percentage of cycle time work elements including and excluding of delays: a. percentage of cycle time work elements including of delays; b. percentage of cycle time work elements excluding delays; c. productive time vs. delay time

3.2. Productivity of Tower Yarders

Delay-free yarding productivity is defined by the following regression equation:

$$P_{\mathrm{PMH}}=6.372-0.339x_1-0.820x_2+3.498x_3-0.338x_4+0.543x_1x_2-0.343x_3x_4+0.302x_4^2 \quad [m^3h^{-1}] \quad (3)$$

Regression Summary for Dependent Variable: $R^2=0.95$, $F(14,75)=101.76$, $p<0.05$, Std. Error of estimate: 0.413.

Therefore, to increase delay-free yarding productivity lateral yarding distance *l*, slope yarding distance *L*, and terrain slope *s* should be at low level (i.e. $x_1=-1$, $x_2=-1$ and $x_4=-1$), whereas the load volume per cycle *Q* will be at high level ($x_3=1$).

The yarding productivity including delays is expressed as:

$$P_{\mathrm{SMH}}=7,064-2.544x_2+3.095x_3+0.622x_4-3.455x_2x_3+1.160x_3x_4-0.775x_1^2-1.496x_3^2 \quad [m^3h^{-1}] \quad (4)$$

Regression Summary for Dependent Variable: $R^2=0.74$, $F(14,75)=15.99$, $p<0,05$, Std. Error of estimate: 0.957.

From equations (3) and (4), reducing at low level the lateral yarding distance *l* (i.e. $x_1=-1$), yarding (inhaul) distance ($x_2=-1$) and increasing to high level the volume of load to the maximum allowed (i.e. $x_3=1$) it could expect that the yarding productivity will rise in this case to 9 m^3 per scheduled machine hour. The mean yarding productivity at shift level (duration of work day of 8 h), excluding and including delays, estimates at 38.82 m^3 per shift and 36.27 m^3 per shift, respectively. Generally, the mean yarding productivity of studied machine per hour and shift level is close to the maximum for that type of cable yarders under given conditions, compare to the rates quoted by Dimitrov (2012), Senturk et al. (2007), Melemez et al. (2014) and Zimbalatti and Proto (2009).

On the other hand, in order to improve the yarder productivity and to use the full load capacity of the carriage, is advisable at least to double the mean load volume per turn (0.67 m^3). This could be achieved, for example, by yarding stems or whole trees instead logs or several logs per turn. In this way, delimbing and bucking operations may be moved from stump to the landing at roadside or machinery equipped with processors may be used. Nevertheless, in this study there was no enough space at the landing to process stems and pile~~s~~ the logs using the motor-manual techniques.

The use of Processor Tower Yarder (PTY) technology is recommended in steep terrain given the improved productivity, which ranges from 90 to 120 m^3 per 8-h day [3]. Such technology enables tree processing, sorting and piling after releasing the load consisting of whole trees [2, 4, 21, 23].

4. Conclusions

The greatest part of cycle time holds inhaul (54% and 47% respectively, excluding and including delays), whereas descending of empty hook is the shortest cycle element (1%). Hook is second by heaviness cycle element (16% and 14% respectively, excluding and including delays). As the tree load mostly drags on the ground during lateral inhaul with mean ground distance of 17.5 m the share of this cycle element is also significant – 10% and 8% respectively, excluding and including delays. The duration of unhook is 8% and 7% respectively, excluding and including delays, due to insufficient landing area.

The productive time for the studied cable yarder was about 87% and operational and mechanical delays accounted respectively for 5.5% and 7.5% of the scheduled machine hour. The mean productivity of tractor-mounted tower cable yarder at shift level is close to the maximum for that type In order to improve the yarder productivity and the full load capacity of the carriage is advisable at least to double the mean load volume per turn by yarding stems or whole trees instead logs. The use of Processor Tower Yarder (PTY) technology in coniferous stands under given terrain conditions is recommended to significantly increase productivity.

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