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Evaluation of Productivity and Cost Analysis on a Combined Logging System

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Abstract: The efficient planning and control of timber harvesting operations is crucial to growth productivity and reducing costs, and different systems or methods are applied to obtain elevated performance. In particular, cable yarding is a highly appreciated and very efficient wood extraction method in areas that are difficult to access with ground-based extraction machines. Combined logging systems are not diffuse and not often implemented. For this reason, the use and the application of innovative methods are limited. However, some combinations have recently been observed in forest operations. This study, conducted in a deciduous stand in Bulgaria, paid attention to the combination of a tractor-mounted tower yarder (Valentini V400) with a clambunk skidder (Timberjack 1010D), aiming to examine the viability and develop the operational efficiency of the two-stage extraction system and to define the time, log volume extracted per unit by the yarder and the clambunk, and the yarding and skidding costs. The researchers carried out a time-motion study and performed a regression analysis to identify those variables that are most likely to affect the duration of work elements and productivity. For cost analysis, the COST model was used. The mean productivity of the tower yarder was 10.34 m^3/PMH and 8.11 m^3/SMH, while for the clambunk skidder, the productivity was 6.23 m^3/PMH and 4.93 m^3/SMH. The net costs for the combined logging system were calculated as 120.87 €/PMH and 14.93 €/m^3. This study adds new data about the correct use of both machines, supporting their application in beech forests.

Keywords: forest operations; skidding; yarding; performances; deciduous stands

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1. Introduction

Cable yarders are an important system of skidding and transporting timber and their use in the mountainous regions of Europe is widespread [1,2].

During the last ten years, the use of all-terrain mobile tower cable cranes has been increasing due to their adaptability in operating both in uphill as well as in downhill configurations. However, modern cable yarding technology fills this gap, and productivity models can assist users in their work, to maximize the performance of their machines [3]. On difficult terrain, cable cranes represent a cost-effective alternative system compared to ground-based logging, and results in a much lower site impact too [4,5]. Over the past two decades, forest operations have been developing timber harvesting guidelines to mitigate the environmental impacts of tree felling and transport. Efficient forest management is essential for the resilience of these ecosystems. The use of this combined logging system helps reduce the effect of timber harvesting [6]. Cable yarders are used mainly for timber harvest using parallel or fan-shaped schemes [7], and new double-hitch carriages have been applied for full suspension. This different method requires longer to load up but permits a similar performance [8].

Worldwide, the principal use of these machines is in coniferous stands and rarely in deciduous stands [9]. Cable yarding in hardwood is widespread in the Appalachians in the Northeast of the US [10–14], southern Germany [1], southern Italy [15,16], Bulgaria [9,17], and Turkey [18]. In Bulgaria the quota of deciduous tree species is 71%, while the quota of total assets growing is 55.5% [19,20]. Therefore, the use of these machines is important in the Bulgarian logging industry. In one example, a cable logging team of three workers tested a yarder for single-span layouts, while a different team of four members worked using both a yarder and skidder [21,22]. In the Northeast US, Huyler and LeDoux [13] found that yarding delays were approximately 35% of the total cycle time for operational, mechanical, and non-productive time descriptions on steep slopes. The delays are separate from the delay-free times used to estimate the total cycle time [13].

To raise the performance of cable yarding worked in European beech (*Fagus sylvatica* L.) stands in the Ograzhden Mountains (southwest Bulgaria), Dimitrov [17] showed that productive times for bunching (28%), extraction (21%), and carriage unloading (13%) should be decreased. In the mentioned paper, the performance of the yarder was defined as moderate (3.22 m^3/PMH). This productivity is comparable with other research carried out in a mixture of Oriental spruce (*Picea orientalis* (L.) Link.), Normann fir (*Abies nordmanniana* (Stev.) Mattf.), and Scots pine (*Pinus sylvestris* (L.) forests in Turkey (6.6 $m^3 \cdot h^{-1}$, 5.5 $m^3 \cdot h^{-1}$, and 5.0 $m^3 \cdot h^{-1}$) [23]. In Italy, Zimbalatti and Proto [15] showed that three cable cranes extracted inferior volumes of timber compared to their load potential; in fact, the average extracted volume was inferior compared to the load capacity of the carriage. Melemez et al. [18] showed that for a slope of terrain greater than 50%, the most efficient extraction occurs by the use of a skyline. The study carried out by Stoilov [9] in a deciduous stand of European beech (90%) and European hornbeam (10%) in the Sredna Gora Mountains, Central Bulgaria, showed that the mean productivity of a truck-mounted tower yarder was close to the maximum for that type (9.12 $m^3 \cdot PMH^{-1}$ and 8.41 $m^3 \cdot SMH^{-1}$). The gross costs for yarding uphill a whole tree by the studied tower yarder were estimated at 146.52 € per PMH and 13.02 € per m^3. Fixed costs (26.84%) and variable costs (29.86%) were higher than labor costs (21.44%).

Most operations may be considered economically skillful if the costs of operations are determined carefully, taking into account all factors in a high-yield stand [10]. Schweier [1] showed that the harvesting costs of two different systems in flat terrains are similar, determining the cost of using a Koller K507 at 33 €$\cdot m^{-3}$, while that of a Valentini V400 cable crane was 36 €$\cdot m^{-3}$. Between the two systems, the Koller K507 was more cost-efficient in processing timber of large dimensions.

Combining a tower yarder with other extraction machines, although known for a long time, is not often implemented [24]. However, such combinations have recently been observed, such as with a clambunk skidder.

The clambunk skidder lends to replacing or being used together with skidders, feller–bunchers, and processors [25]. Stokes and Schilling [26] have demonstrated that clambunk skidders mitigate the adverse effects of operations on conventional and challenging sites, while also enhancing the efficacy of the harvesting system. The use of this machine is more advantageous as the extraction distance and number of passes over the site increase, reducing road construction. On a clambunk skidder, the load is positioned on an integrally mounted loader and it is held by top-opening jaws [27]. In South Africa, Oberholz [28] has obtained a productivity of 5.7 m^3/PMH to 50 m^3/PMH in pine stands using a clambunk skidder with a capacity of 18 t, with uphill slopes 0%–25%, downhill slopes 0%–40%, and skidding distances of 50–1000 m. The variable, fixed, and administration costs were the most significant for cost analysis. Clambunk production costs differed with skidding distance because this variable involved travelling times. In Brazil, Dos Santos et al. [29] have studied the average harvesting cost of a clambunk skidder in a stand of eucalyptus. It was equal to 1.7 €$\cdot m^{-3}$, for an average distance of extraction of 241.23 m with a volume average of 0.39 $m^3 \cdot tree^{-1}$. This cost ranged from R$3.14 to R$6.93 m^{-3} (around 1.10 to 2.40 €$\cdot m^{-3}$) for extraction distances of 106 m and 366 m, respectively [29]. In a study, Ghaffariyan [30] reported an average productivity varying from 9.3 m^3/PMH to 78.0 m^3/PMH in coniferous forests and plantations. The type of machine, the volume of logs, the slope of the terrain, and the skidding distance affect the performance of the skidder.

The aim of this present study was to examine the viability and to improve the use and operational efficiency of the two-stage extraction system, consisting of a tractor-mounted tower yarder and clambunk skidder in deciduous stands, and to analyze the time consumption, harvesting productivity, and costs for both machines. The adoption of these machines is useful for improving the economic and environmental performance of wood harvesting in deciduous forests, also involved in the Natura 2000 network.

2. Materials and Methods

2.1. The Study Site

This research was conducted in the Vitinya State Hunting Range (Figure 1), sited in the Western Balkan Mountains, Sofia Province (Table 1). This study focused on the Valentini V400 (Valentini srl, Cles, Italy) tractor-based tower yarder and Timberjack 1010D (Deere & Company, Moline, IL, USA) single-drum cable + clambunk skidder shown in Figures 2 and 3.

Table 1. Technical data of research area.

Location	Subcompartment 91-v N 42°49′9.788″; E 23°43′7.0468″
Elevation	1300 m asl
Forest tree	European beech (*Fagus sylvatica*, L.) 100%
Stand age	90 years
Silvicultural system	High natural forest
Total area	12.0 ha
Cutting area	10.0 ha
Silvicultural intervention	Thinning, removal intensity 15%
Average tree height	21 m
Average DBH of tree	30 cm
Average slope	29° (55%)
Volume site	3580 m^3 (334 $m^3 \cdot ha^{-1}$)
Extraction direction	Uphill

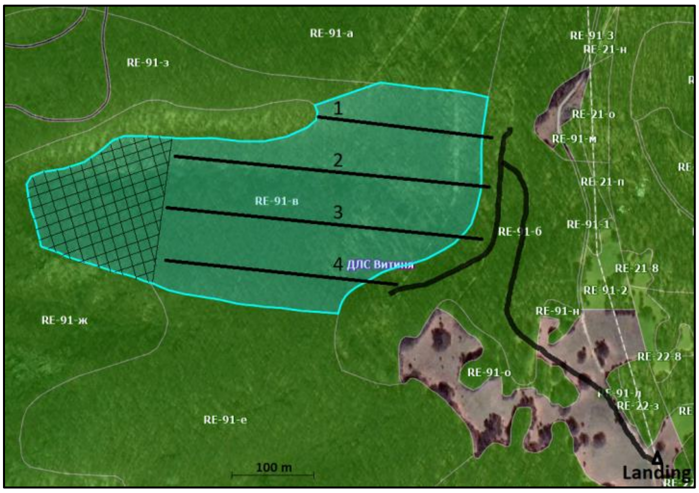

Figure 1. Location of case study (—skidding road; —tower yarder skyline; Δ—landing). ДЛС Витиня means Vitinya State Hunting Range.

Figure 2. Valentini V 400 tractor-based tower yarder.

Figure 3. Timberjack 1010D clambunk skidder.

2.2. Description of the Machines, Work Team, and Time Study

To start with harvesting operations, trees were felled, delimbed, and crosscut into stems and stem sections. Wood materials in the stems and logs were extracted initially by the Valentini V400 tractor-mounted tower yarder to the skidding road and from there transported semi-suspended by the Timberjack-1010D clambunk skidder to the landing. To avoid the yarded stems sliding back into the cutting area, they were hauled by the clambunk skidder with its built-in single drum winch and then loaded at their thick ends into the clambunk using the hydraulic crane. The personnel of both machines consisted of 3 workers: a tower yarder operator, choker-setter, and clambunk skidder operator. All had more than 5 years of experience and were aged 40–50. Technical data of the studied machines are shown in Tables 2 and 3. As shown in Figure 1, four parallel-shaped corridors were created with the following lengths and slopes: Corridor 1—220 m, 14° (25%); Corridor 2—400 m, 19° (34%); Corridor 3—400 m, 19° (34%); and Corridor 4—320 m, 17° (31%). For each corridor, 30 cycle times were monitored, and 120 turns were collected during forest operations. A single-span uphill configuration was monitored in each detailed phase. The longitudinal slope of the skidding road in the section from Corridor 4 to midway between Corridor 2 and Corridor 1 at the tower yarder averages 11° (19%) uphill. In the section to the landing it is 3° (5%), also uphill, which, however, is not much slope resistance to the operation of the dedicated clambunk skidder.

Table 2. Technical data of Valentini V400 tractor mounted tower yarder.

Parameter	Value
Skyline	
Length/cable diameter	400 m/16–17 mm
Pulling force	67 kN
Mainline	
Length/cable diameter	400 m/10 mm
Pulling force	21–28 kN
Pulling speed	3–4.5 m/s (10.8–16.2 km/h)
Guylines	4(5) × 60 m, Ø14 mm
Tower height	10 m
Base machine	Belarus 1221.3 farm tractor (96 kW)
Diesel engine power	Minimum 89 kW (120 hp)
Weight of tower yarder (incl. cables)	3800 kg

Table 3. Technical data of Timberjack 1010D clambunk skidder.

Parameter	Value
Engine type:	John Deere 4045 HTJ76
Rated power	86 kW at 2000 min^{-1}
Maximum net torque	498 Nm at 1400 min^{-1}
Transmission	Hydrostatic-mechanical transmission with low and high range
Travel speeds forward and reverse	High: 0–22 km/h; Low: 0–8 km/h
Max. tractive effort	140 kN
Sizes:	
Length	9.05 m
Width	2.70 m
Transport height	3.70 m
Ground clearance	605 mm
Wheelbase	4.80 m
Load capacity	11,000 kg
Operating weight	12,700–13,700 kg
Max. load rating	10,000 kg
Crane:	CF5
Gross lifting torque	102 kNm
Winch	One-drum
Cable length	65 m
Nominal pulling force of winch	50 kN

The tower yarder work cycle was divided into several elements [31–34]. Six work elements were separated and considered to estimate the work cycle time [13]; they were like those described by Proto and Zimbalatti [16]:

- Carriage outhaul (CO);
- Lateral outhaul and hook (LOH);
- Lateral inhaul (LI);
- Carriage inhaul (CI);
- Unhook (U);
- Delay time (D).

The work phase of the clambunk skidder has been divided into the following 8 elements:

- Travel unloaded (TU);
- Maneuvering (M);
- Winching (W);
- Loading (LOAD);
- Travel loaded (TL);
- Unloading (UNLOAD);
- Sorting and piling (SP);

- Delays (DS).

2.3. Costs Analysis

Machine costs for the extraction of 1 m^3 of wood materials were calculated according to the COST model [35] based on the parameters as follows: number of operators, operator costs per hour, and productive machine hours (PMHs) (without delays). Hourly machine costs are given in both PMHs and scheduled machine hours (SMHs), including delays. Purchase costs and operator wages were sourced from catalogs and accounting documents [33]. Fuel costs were determined with the refilling fuel tank method provided before operations and accounting for the fuel used by topping up at the end of the workday. The costs of the tested machines were based on assuming that companies in the logging industry work on average 150 days per year, distributed on 20–21 working days per month, an average of 5–6 actual working hours per day, not considering the time needed for day meals. Therefore, the machines work 910–1050 scheduled hours within a year at a use coefficient of 70% [36,37].

2.4. Data Analysis

A time and motion study is carried out to find the duration of work items and productivity. Thus, those variables that are most likely to influence them are determined. Each phase is timed with a stopwatch and the effective time is separated from the delay time. Yarding and skidding distance were counted by a GPS. Winching distances and terrain slopes were measured with a professional laser range finder with a built-in clinometer. The volume of the single skidded logs was assessed using the Huber formula. Regression analysis of the experimental data was performed to obtain equations for predicting the dependent variables of duty cycle time and machine productivity. The independent variables that were used to model the yarder were as follows: yarding distance L_{TY}, lateral yarding distance l_Y, load volume per cycle V_{TY}, terrain slope angle i, and the load's number of trees n_{TY}. Information on the independent variables skid distance L_{CS} as well as number n_{CS} and stem volume V_{CS} were used to model skidder performance.

Descriptive statistics of the variables were found and stepwise backward regression was used to model the variability of duty cycle time and machine productivity based on independent variables. The normal distribution of the experimental data values was established using the Kolmogorov–Smirnov (K–S test) and Shapiro–Wilk tests.

A confidence level of 95% ($\alpha = 0.05$) and an assumed probability of $p < 0.05$ were used for regression analysis. Independent variables are significant at $p < 0.05$, i.e., a strong presumption against the null hypothesis. Statistica 8 software (StatSoft Inc., Tulsa, OK, USA) was used to process the experimental data.

3. Results and Discussion

The summary of the experimental data from 120 yarding and 30 clambunk skidder cycles for each of the selected variables used in the cycle time and production equations is shown in Table 4.

Table 4. Average field data collected.

Variables	Cycle Time, Minutes			Distance, m		
	Mean Value ± St. dev.	Min	Max	Mean Value ± St. Dev.	Min	Max
Yarding						
Carriage outhaul (CO)	0.72 ± 0.089	0.60	0.90	123.83 ± 17.47	90	150
Lateral outhaul and hook (LOH)	3.49 ± 0.54	2.20	4.60	12.84 ± 3.29	6	22
Lateral inhaul (LI)	0.36 ± 0.047	0.25	0.43	12.84 ± 3.29	6	22
Carriage inhaul (CI)	0.86 ± 0.11	0.70	1.08	123.83 ± 17.47	90	150
Unhook (U)	0.40 ± 0.087	0.25	0.50			
Delays (DY)	7.72 ± 13.16	0.33	33.22			

Table 4. *Cont.*

Variables	Cycle Time, Minutes			Distance, m		
	Mean Value ± St. dev.	**Min**	**Max**	**Mean Value ± St. Dev.**	**Min**	**Max**
Total cycle time (T_{TY})	13.68 ± 13.62	5.07	39.15			
Delay-free cycle time ($T_{net,TY}$)	6.04 ± 0.71	4.63	7.55			
Load volume per cycle (turn), m^3	1.01 ± 0.33	0.75	1.91			
Productivity, m^3 per PMH	10.34 ± 2.07	7.20	17.63			
Productivity, m^3 per SMH	8.11 ± 3.83	1.17	15.15			
Number of stems per cycle	1.43 ± 0.50	1	2			
Skyline slope, deg	17.25 ± 2.05	14	19			
Number of cycles per SMH	7.66 ± 3.53	1.53	11.84			
Skidding						
Travel unloaded (TU)	6.08 ± 1.37	3.88	7.50	693.03 ± 180.38	467	870
Maneuvering (M)	0.35 ± 0.12	0.17	0.58			
Winching (W)	22.61 ± 6.72	6.73	38.50			
Loading (LOAD)	2.55 ± 0.15	2.32	305			
Travel loaded (TL)	12.46 ± 2.29	8.67	15.00	693.03 ± 180.38	467	870
Unloading (UNLOAD)	2.32 ± 0.08	2.15	2.50			
Sorting and piling (SP)	2.23 ± 0.12	2.00	2.40			
Delays (DS)	12.51 ± 1.43	10.33	16.47			
Total cycle time (T_{CS})	61.11 ± 7.63	46.97	79.27			
Delay-free cycle time ($T_{net,CS}$)	48.60 ± 8.00	32.02	68.27			
Productivity, m^3 per PMH	6.23 ± 1.35	3.85	10.23			
Productivity, m^3 per SMH	4.93 ± 1.11	2.77	8.37			
Number of stems per cycle	6.63 ± 1.22	3	9			
Number of cycles per SMH	1.00 ± 0.13	0.76	1.28			
Speed loaded, km·h^{-1}	3.30 ± 0.38	2.56	3.82			
Speed unloaded, km·h^{-1}	6. 82 ± 0.58	4.42	7.45			
Mean speed, km·h^{-1}	4.44 ± 0.43	3.63	5.02			

3.1. Duration of Work Cycle Elements—Tower Yarder Unit

The work phases of the tower yarder (Figure 4) were subdivided into the following times (including delays): lateral outhaul and hook (LOH) occupied 26% of the time, followed by carriage inhaul (CI) 6%, carriage outhaul (CO) 6%, unhook (U) 3%, and lateral inhaul (LI) 3%, respectively. The percentages of times excluding delays were as follows: LOH occupied 60% of the time, CI 14%, CO 13%, U 7%, and LI 6%, respectively. The predominant part of the cycle time (Figure 1), excluding and including delays, was dedicated to the lateral outhaul and hooking (LOH) of the tree (60% and 26%, respectively), followed by carriage inhaul (14% and 6%, respectively) and carriage outhaul (13% and 6%). The other phases had approximately similar proportions: unhook (7% and 3%, respectively) and lateral inhaul (6% and 3%, respectively), excluding and including delays. Delays accounted for 56% of the total phase time and could be divided into operational and mechanical delays, respectively, for 52% and 4% of the total phase time of the studied cable yarder machine. Operational delays, 92% of all delays of the tower yarder, were predominantly due to the clambunk work phase (travel loaded to landing, unloading, sorting and piling, and travel unloaded). Within this time, the tower yarder can only make one phase (turn), waiting for the clambunk skidder to winch the extracted stems, due to the danger of them sliding back to the cutting area. A total of 66% of the work phase time, without delays, involved operations of lateral yarding (29% including delays). These operations include the lateral pull of the main line and the extraction of the load. In these conditions, the machine works at a moderate and low level of carriage payload capacity usage, with an average yarding distance of 123.83 m from nominal length, an average lateral yarding distance of 12.84 m, and an average slope of 17.25°. To estimate the yarding phase time (with and without delays), a regression analysis on time data was performed to create a prediction equation, using the independent factors in Table 4. The delay-free cycle time

(Equation (1)) and the cycle time with delays regression models (Equation (3)) obtained for cable extraction with significant factors are displayed in Table 5. In Equation (1), the minimum values of $T_{net,TY}$ may reach for this eventuality lower rates of yarding distance L_{TY} and terrain slope angle *i*. The total cycle time of the tower yarder (Equation (3)) will decrease as the yarding distance L_{TY} is decreased and the lateral yarding distance *l* and the number of load stems n_{TY} are increased.

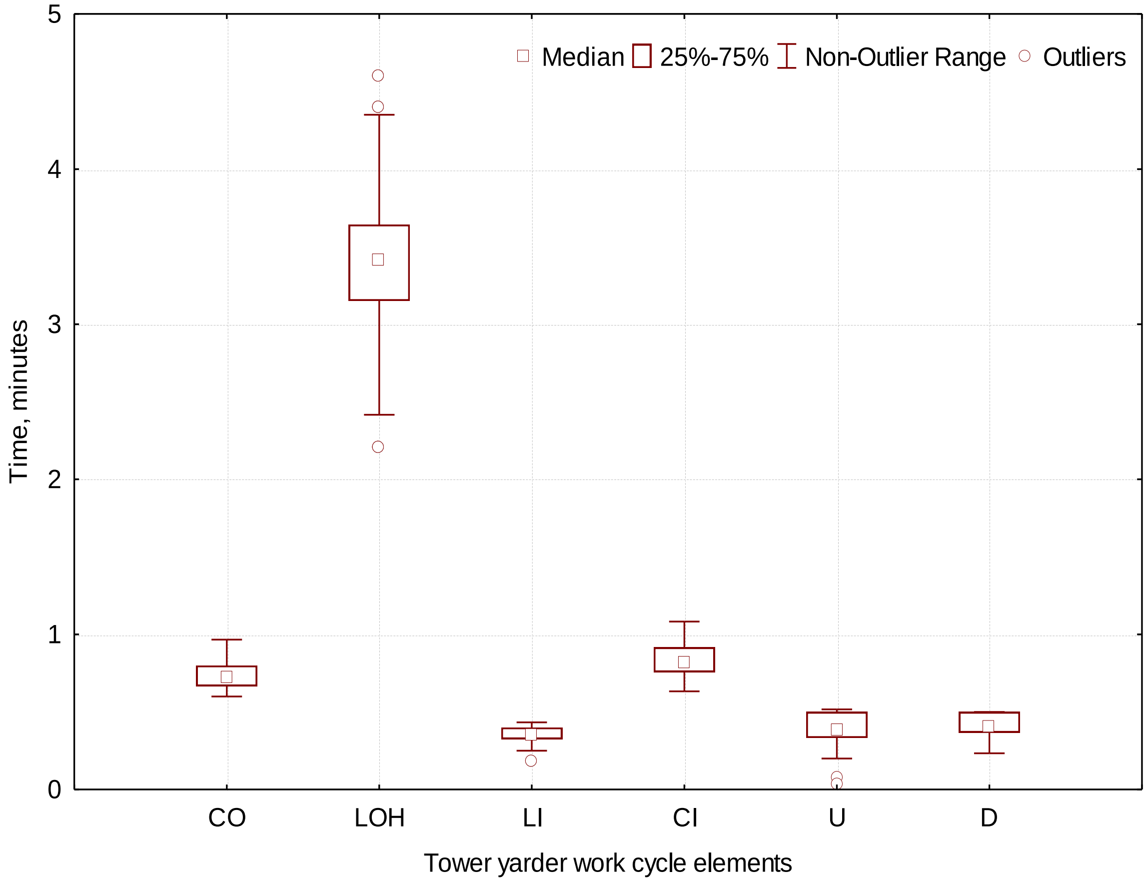

Figure 4. Elemental time consumption of tower yarder unit. Note: CO—carriage outhaul, LOH—lateral outhaul and hook, LI—lateral inhaul, CI—carriage inhaul, U—unhook, D—delays.

Table 5. Work cycle time prediction models.

Equations	*F*	R^2	R^2_{adj}	SE	*p*-Value
$T_{net,TY} = 1.88 + 0.026 \cdot L_{TY} + 0.053 \cdot i$. (1)	36.01	0.38	0.37	0.59	<0.05
$T_{net,CS} = 26.84 + 0.028 \cdot L_{CS} + 3.15\ n_{CS}$. (2)	18.11	0.57	0.54	5.21	<0.05
$T_{TY} = 0.26 \cdot L_{TY} - 1.44 \cdot l - 6.08 \cdot n_{TY}$. (3)	10.50	0.21	0.19	32.32	<0.05
$T_{CS} = 0.29 \cdot L_{CS} + 3.64 \cdot V_{CS}$. (4)	21.04	0.61	0.58	5.30	<0.05

Note: $T_{net,TY}$—delay-free cycle time, tower yarder; L_{TY}—yarding distance, tower yarder; *i*—terrain slope angle; $T_{net,CS}$—delay-free cycle time, clambunk skidder; L_{CS}—skidding distance; n_{CS}—number of stems; T_{TY}—total cycle time, tower yarder; *l*—lateral yarding distance; n_{TY}—load's number of trees; T_{CS}—total cycle time, clambunk skidder; V_{CS}—load volume per phase, clambunk skidder.

3.2. Duration of Work Cycle Elements—Clambunk Skidder

The clambunk skidder work cycles (Figure 5) were subdivided into the following (including delays): winching (W) occupied 36% of the time, followed by travel loaded (TL) 22%, travel unloaded (TU) 11%, loading (LOAD) 4%, unloading (UNLOAD) 3%, sorting and piling (SP) 3%, and maneuvering (M) 1%, respectively. The percentages of time excluding delays were as follows: W occupied 45% of time, TL 27%, TU 14%, LOAD 5%, UNLOAD

4%, SP 4%, and M 1%, respectively. The delays accounted for 19% of the total cycle time and are divided into operational and mechanical delays, respectively, for 16% and 3% of the total cycle time of the clambunk skidder. The operational efficiency obtained during the study of the Timberjack 1710 clambunk skidder extracting whole eucalyptus trees for chipping was 78.30%, while mechanical availability was 87.38% [29]. From Table 5, the delay-free clambunk skidder cycle time $T_{net,CS}$ regression model (2) shows that a reduction can be achieved by reducing the number of stems n_{CS} in the payload. The same conclusion applies to the total cycle time of the clambunk skidder T_{CS} given by Equation (4). Within the subdivision of operations of the clambunk skidder (excluding delays), winching (36%), and movement (34%) took up the most time, followed by loading and unloading (7%) and sorting and piling at landing (3%). The mean speed of the studied clambunk skidder was 4.25 km·h^{-1}. The clambunk skidder with a load had an average speed of 3.23 km·h^{-1}, and an average of 6.28 km·h^{-1} without a load. The difference is 3.05 km·h^{-1}—almost double the unloaded weight since the skidding resistance forces of the rear parts of the stems do not act when moving without a load.

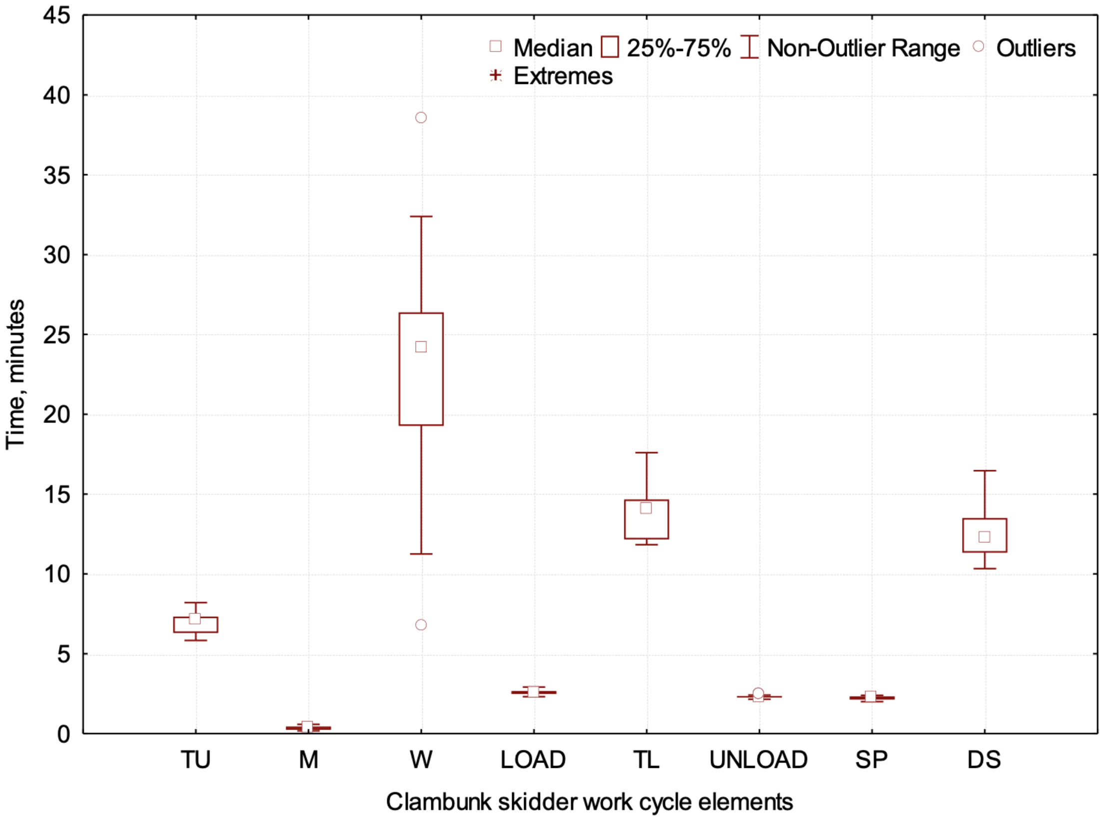

Figure 5. Elemental time consumption of clambunk skidder. Note: TU—travel unloaded, M—maneuvering, W—winching, LOAD—loading, TL—travel loaded, UNLOAD—unloading, SP—sorting and piling, DS—delays.

Orlovský et al. [38], for an LKT 81 ILT cable skidder with knuckle-boom, stated an average speed of 3.75 km·h^{-1} with load, and an average speed of 4.45 km·h^{-1} without load, i.e., lower than the values we found. However, Spinelli and Magagnotti [39] reported an average speed of 8.1 km·h^{-1} without load and an average speed of 7.3 km·h^{-1} loaded travel, for a 96 kW agricultural tractor, significantly higher than this study. Also, for a John Deere 548H, the average speed was 8.60 km·h^{-1} and 6.00 km·h^{-1}, respectively, for travel loaded and unloaded [38]. To reduce movement time, the clambunk skidder should increase its travel speed. Unfortunately, the terrain conditions do not afford a significant increase in speed.

3.3. Productivity Analysis

The productivity of the studied machines was described by the regression equations (Table 6). The tower yarder productivity (without delays), described by Equation (5) in Table 6, can be increased by reducing distance and skyline slope and increasing load volume. The same can be said for tower yarder productivity including delays (Equation (6)) by reducing lateral yarding distance. Another option is a truck-based yarder with a hydraulic crane with a grapple to place the yarded stems on the road. If the hydraulic crane is equipped with a processor head, crosscutting and subsequent forwarding of assortments (logs) is possible. In these two cases, one will move from a serial to a parallel production system.

Table 6. Productivity prediction models.

Equations	F	R^2	R^2_{adj}	Std. Error	p-Value
$P_{PMH,TY} = 7.63 - 0.041 \cdot L_{TY} - 0.11 \cdot i + 9.67 \cdot V_{TY}$, $m^3 \cdot h^{-1}$ (5)	110.48	0.74	0.73	1.07	$p < 0.05$
$P_{SMH,TY} = 9.11 - 0.084 \cdot L_{TY} + 0.36 \cdot l + 3.39 \cdot n_{TY}$, $m^3 \cdot h^{-1}$ (6)	22.50	0.37	0.35	3.08	$p < 0.05$
$P_{PMH,CS} = 4.42 - 0.0036 \cdot L_{CS} + 0.84 \cdot V_{CS}$, $m^3 \cdot h^{-1}$ (7)	63.27	0.91	0.81	0.61	$p < 0.05$
$P_{SMH,CS} = 2.35 - 0.0021 \cdot L_{CS} + 0.79 \cdot V_{CS}$, $m^3 \cdot h^{-1}$ (8)	106.40	0.89	0.88	0.40	$p < 0.05$

Note: $P_{PMH,TY}$—productivity machine hours, tower yarder; L_{TY}—yarding distance, tower yarder; i—terrain slope angle; V_{TY}—load volume per phase, tower yarder; $P_{SMH,TY}$—scheduled machine hours, tower yarder; l—lateral yarding distance; n_{TY}—load's number of trees; $P_{PMH,CS}$—productivity machine hours, clambunk skidder; L_{CS}—skidding distance; V_{CS}—load volume per phase, clambunk skidder; $P_{SMH,CS}$—scheduled machine hours, clambunk skidder.

From Equation (7), to increase the clambunk skidder delay-free productivity, the load volume per phase V_{CS} should be increased, whereas the skidding distance L_{CS} in it should be decreased. The clambunk skidder productivity including delays is calculated by Equation (8) in Table 6, and the opportunities for increase are the same as for delay-free productivity.

Consequently, the productivity models indicate skidding distance and load volume extracted per phase (turn) as the most important factors affecting the skidding productivity of the studied clambunk skidder in the conditions of thinning in European beech forests. Of course, further studies could evaluate the influence of other variables to compare productivity in several stands.

The average productivity, obtained at an average skidding distance of 693 m, average load volume per cycle of 5.02 m^3, and mean 6.6 stems per phase (turn), is 6.23 $m^3 \cdot PMH^{-1}$ and 4.93 $m^3 \cdot SMH^{-1}$ respectively.

These productivity rates are close to those reported by Orlovský et al. [38] for the LKT 81 ILT with knuckle-boom loader, which, at an average skidding distance of 316 m and mean load volume per phase of 8.00 m^3, are 6.31 $m^3 \cdot PMH^{-1}$ and 4.20 $m^3 \cdot SMH^{-1}$, respectively. Borz et al. [40] determined a higher value of productivity in terms of PMH and SMH (4.40 $m^3 \cdot h^{-1}$ and 3.10 $m^3 \cdot h^{-1}$, respectively) testing a TAF 690 skidder covering an average distance of 1700 m. The mean productivity for a TAF 690 PE in similar terrain conditions and a shelterwood system obtained by Stoilov et al. [24] was 16.0 $m^3 \cdot PMH^{-1}$ and 14.00 $m^3 \cdot SMH^{-1}$, respectively, for an average distance of 264 m (2.6 shorter than that in this present study), mean load volume of 3.94 m^3 (1.3 lower than that in this present study), and mean 2.2 logs per travel.

For the John Deere 548H skidder, Proto et al. [37] registered a harvesting performance of 30.5 m^3 per PMH and 25 m^3 per SMH in conditions of an average seven logs extracted per turn, at a mean extraction distance of 275 m, average and maximum winching distances, respectively, of 35 and 65 m, and a mean volume skidded per cycle of 3.90 m^3.

The tower yarder and clambunk skidder present a serial production system. In the serial system the production processes are performed individually in sequence [41], since after the stems are extracted by the tower yarder, the skidding process starts.

The use of the serial production system for timber extraction allows both machines to be used more rationally and thoroughly, and, consequently, increases their productivity, improves the technical maintenance of equipment and current repairs, ensures the possible full compliance of forestry equipment with natural production conditions, and, ultimately, increases the efficiency of logging production. For a serial production system of machines to be effective in specific terrain and production conditions, it must be designed in such a way that their productivity must be equal or multiple and efficient for a given volume of production. This study ensures the full rate of utilization of equipment, reduces production costs, and allows for reducing manual labor in the forest stand to the minimum possible, i.e., only until felling, delimbing, pulling, and hooking the stems to the yarder mainline. The majority of operations are carried out at convenient workplaces near forest roads and landings, which reduces the risk of occupational injuries. In addition, the use of the forwarder crane supports the bucking, sorting and piling of the received assortments on the landing.

Therefore, by equating the delay-free productivity models of the two machines, parameter values can be determined. The effect of the yarding distance L_{TY} on the skidding distance L_{CS} for a skyline slope of 17° and carriage payload of 1 m^3 is shown in Figure 6a.

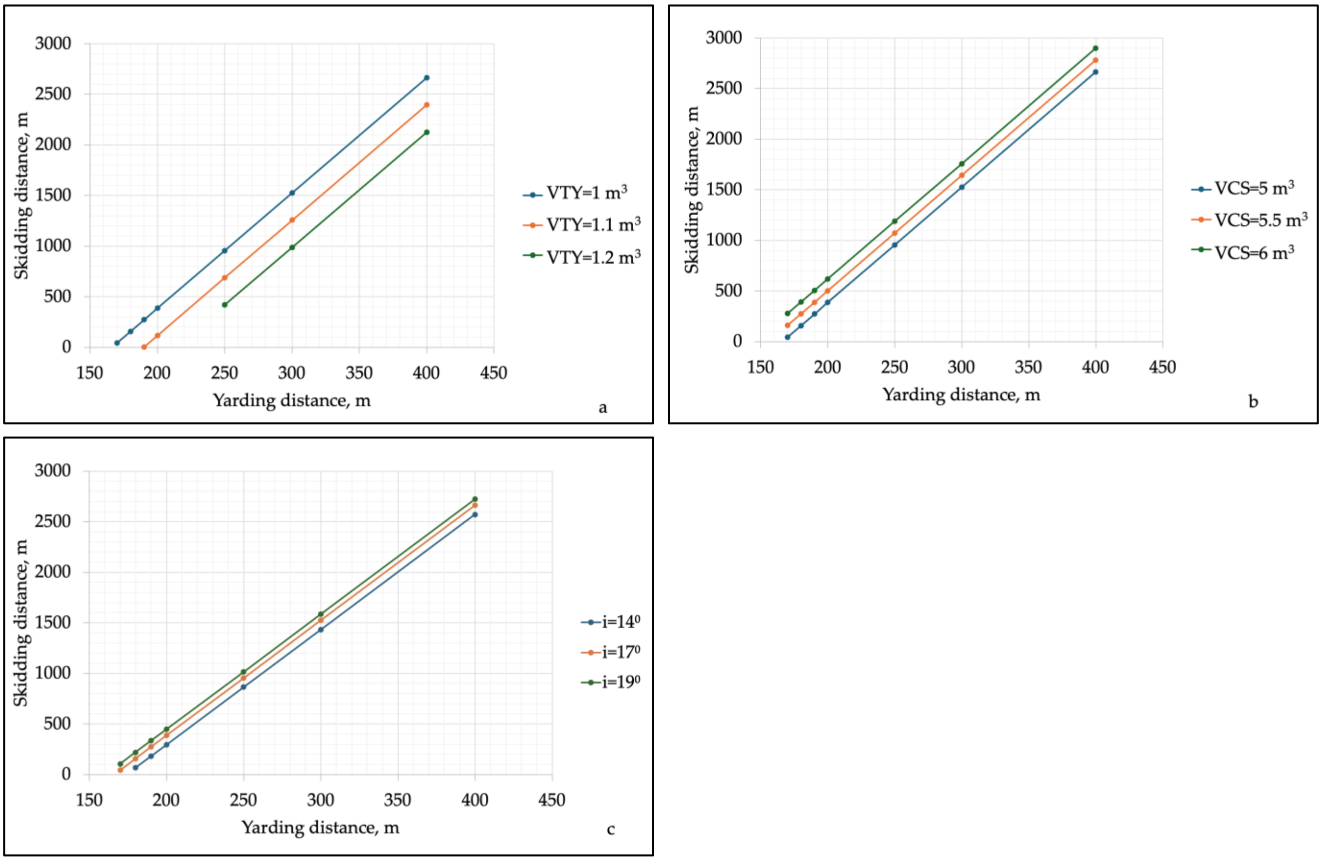

Figure 6. (**a**–**c**) Different parameters influenced by yarding distance and skyline slope. Note: VTY—load volume per phase, tower yarder; VCS—load volume per phase, clambunk skidder, *i*—terrain slope angle.

An increase in yarding distance and skidder payload results in an increase in skidding distance where delay-free productivity is equal. An increase in carriage payload has a similar effect on the skidding distance at constant values of skyline slope of 17° and skidder payload of 5 m^3 (Figure 6b). The influence of skyline slope with other parameters constant is shown in Figure 6c. Increasing the skyline slope, other parameters being constant, leads to a decrease in delay-free yarding productivity, but an increase in the corresponding skidding distance.

3.4. Costs

The extraction net costs of the studied production system for stem yarding and skidding in a beech stand were calculated at 120.87 € PMH and the harvesting costs at 14.93 €/m^3 (Table 7). The gross extraction costs of a Koller K501 for cutting trees in a predominantly beech stand were calculated at 13 €/m^3 [9], slightly lower than that of the tower yarder and clambunk skidder studied here. The net extraction costs of a Timberjack 1010D combi–forwarder in similar production and terrain conditions were estimated at 4.1 €/m^3 [20], which is three times lower.

Table 7. Extraction costs.

Classification of Costs	Costs per Hour, € h^{-1}		
	Valentini V400	**Timberjack 1010D**	**Production System**
Purchase price	130,000	25,000	155,000
Total fixed costs:	21.08	10.79	31.27
Depreciation	5.85	7.50	13.35
Interest	3.93	0	3.93
Insurance	9.67	0.74	10.41
Garaging	0.74	0.74	1.48
Taxes	0.15	0.07	0.23
Machine transfer	0.74	0.74	1.48
Total variable costs:	23.63	25.66	49.29
Fuel and lubricants	15.53	15.53	31.06
Tires and tracks	0.60	2.64	3.24
Maintenance and repair	4.55	7	11.55
Winch cables and choker cables	2.95	0.49	3.44
Labor costs	26.66	13.2	39.86
Net costs	71.37	49.5	120.87
Net costs, € per m^3	6.90	8.03	14.93

Note: The purchase price of the Valentini V400 includes the price of the tractor.

In comparison, Proto et al. have determined that the costs of skidding for a John Deere 548H skidder in chestnut stands in South Italy were between 3.6 and 5.8 €·m^{-3} (for an average distance reaching between 266 and 276 m, an average load between 3.88 and 4.01 m^3, and an average slope of 27%) [37]. In Kardzhali Province (Bulgaria), Stoilov et al. [42] reported an extraction cost of an HSM 805 ZL double-drum cable skidder equal to 14.24 €·m^{-3} in a stand of conifers (for an average distance of 69 m, an average load 4.06 m^3, and an average slope of 34%).

In general, these costs are slightly above the extraction costs reported with other machines in this region. This is probably due to the lower performance of the studied extraction system, due to longer delays.

4. Conclusions

The studied extraction system has many advantages. Very often, on steep terrains, in the absence of sufficient landing space, logs which were obtained in a cutting area under difficult working conditions are yarded. The yarder's unloading area must be cleared after each turn for new carriage loads. In the case studied, the yarded stems are pulled with the winch of the skidder. Otherwise, they will inevitably fall back into the clearing. It is also possible to pull the stems with an additional winch or tractor, even with animal power.

The studied system allows for the extraction of stems or stem sections, which reduces operations in clearing, felling, and delimbing, and the remaining operations of crosscutting, sorting, and piling are performed after skidding on the landing under more convenient working conditions.

A disadvantage of the studied extraction system is the long delays due to the skidder waiting for a sufficient load to be collected, and subsequently, during skidding, the yarder waits with the extracted load on the carriage for the skidder to return to pull the load onto the skid road.

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