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ORIGINAL RESEARCH

Forest Operations Using a Combi–Forwarder in Deciduous Forests

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Abstract

In the last decade, technological innovation in the forest operations sector has allowed levels of mechanization alternative to agricultural tractors and animal logging. These machines are used to load logs from skid roads and move logs to the next pile, until the load space is fully loaded. Fortunately, in recent years the development of new technological progresses in forestry mechanization created an alternative operation on ground-based system with the use of a combi-forwarder for wood forwarding. These innovative machines have the advantage that only one machine can perform logs bunching and primary transport. Infact, pull stems by the winch from the stump to the road, after they have been cross-cutted by chainsaws, it loads by the forwarder's crane the logs and transports them to the landing, where they are unloaded with the crane in piles.

The aim of the present study was to analyse the operational time consumption, to estimate the productivity of the combi–forwarder with a built-in single-drum winch in beech stands evaluating the forwarding and winching distances, log's volume transported per turn by the machine, as well as the extracting costs. The study was conducted in low-intensity shelterwood cuttings in beech forest, located in Western Balkan Mountains, Bulgaria.

The mean productivity of the combi–forwarder was 7.09 m^3 PMH^{-1} and 6.11 m^3 SMH^{-1} close to that of the cable skidders and forwarders in similar conditions. The net costs for the studied combi–forwarder were calculated of 25.33 € per productive machine hour and 4.13 € per m^3. The variable costs (70%) have a leading role, followed by labour costs (22%) and fixed costs (8%). The use of a combi-forwarders facilitates chainsaw operators, as some of the operations are carried out at the roadside in better working conditions: flat terrain and support of the crosscutting phase. The results from the study are useful to introduce and to integrate the combi–forwarders with shelterwood systems and to achieve economic and environmental efficiency of timber harvesting in deciduous forests.

Extended author information available on the last page of the article

Keywords Productivity · Skidding · Ground-based machine · Forwarding · Performance

Introduction

Forwarders are the most used ground-based machineries to extract the wood around the world (Lindroos et al. 2017; Borz et al. 2021) and represent a mechanized alternative to agricultural tractors and animal logging (Proto et al. 2018a; Borz et al. 2019). These self-propelled forwarders were first introduced in the 1960s for use in the transport of logs as part of harvesting operations (ISO 6814 2009 - Machinery for forestry — Mobile and self-propelled machinery — Terms, definitions and classification) and are used today in partly mechanized systems that integrate motor-manual felling and processing of trees. The actual concept of forwarders has not changed significantly compared to the original ones, but a significant progress in forwarding machines development has been achieved in key areas, such as the ergonomics, environmental impact and automation (Spinelli et al. 2003; Pandur et al. 2009; Stankić et al. 2012; Apăfăian et al. 2017; Borz et al. 2021). Modern forwarders are an effective forwarding option for timber harvesting operations that provide the opportunity for higher levels of mechanization and thanks to their ability to carry logs from the forest to the roadside or processing areas, some authors have identified lower environmental impacts in comparison to tree-length skidding options (Spinelli et al. 2014; Proto et al. 2018c; Borz et al. 2023). In the same time other studies, however, have found opposing results. Gondard et al. (2003) assessed the impacts on soil surface of clear-cutting in Aleppo pine (*Pinus halepensis*) using both forwarders and skidders, observing that skidders created more disturbances than forwarders and the majority of these disturbances were shallow and not long-lasting. Similar results were reported by Deconchat (2001) in mixed oak coppices. In this study, the observed greater soil disturbance was due to skidders, though skidders were responsible for less than 1% of ruts. These studies make the scientific debate on some environmental impacts between skidders and forwarders still unresolved. The use of forwarders requires mainly the cut-to-length (CTL) systems that offer several advantages compared to other ground-based systems: less road construction, lower levels of soil disturbance, smaller landing sizes due to reduced processing requirements, minimal damage to the logs during handling and forwarding and fewer workers (Bettinger and Kellogg 1993; Picchio et al. 2020).

Forwarder productivity has been widely studied in Europe (Cadei et al. 2020). Several studies have demonstrated that the productivity of this system depends on the forest stand, site and operational factors such as ground conditions, slope, operator skill, branch size, operational layout, tree volume, tree form, log assortments processed, numbers of merchantable trees per unit area, hauling distance, undergrowth density and machine design (Stampfer 1999; Spinelli et al. 2002; Apăfăian et al. 2017). In recent decades, the fully mechanized cut-to-length timber harvesting system has become widely used in many industrialized European countries where the conditions and the stands are favourable, such as in Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%), as compared to motor-manual harvesting (Karjalainen et al.

2001; Mologni et al. 2019; Papandrea et al. 2023). In Austria, where forests are predominantly on mountainous terrains, the distribution of timber harvesting machines from stand to landing in 2009 was: cable yarders – 20%, skidders – 49%, forwarders – 26%, and other means – 5% (Holzleitner et al. 2011). Ten years later, in 2019, this ratio changed in favour of forwarders: cable yarders – 19%, skidders – 37%, forwarders – 43%, and other means – 5% (Prem and Bauer 2020). The important role and diffusion of this forest machine is supported by a large number of studies (Tiernan et al. 2004; Nurminen et al. 2006; Proto et al. 2018b; Cataldo et al. 2022) that are still conducted to test the performance of these machines. Among the first, Sever (1988) determined that travel distance is the most important factor, while Manner et al. (2013) identified log concentration as an influential parameter on the forwarding time consumption; in fact, the movement time during the loading significantly decreases with increasing concentration of the logs. Slugeň and Stoilov (2009) evaluated the slope of 47% as the upper limit for the use of forwarders and harvesters to obtain high productivity in regenerative cuttings and thinning operations, while they found that the productivity between forwarders with different payloads decreased with forwarding distance, both in final felling and thinning. In Bulgaria, as in other European countries (Italy, etc.), although the forest areas are predominantly located on steep terrains with complex shapes, adapted agricultural tractors with logging equipment are predominance and forwarders are not widespread (Proto et al. 2018a; Stoilov 2021a). In particular, in these countries, logs are skidded from the harvest area to the landing on the closest skid road/skid trail using a ground extraction system with a farm tractor and winch or animal force and only after, the forestry trailers, forwarder, or other machines loads the logs from one pile and moves to the next pile, until the load space is fully loaded. Often, this limit is mainly due to the type of cut (thinning, selective, or shelterwood) which does not allow the forwarder to enter in the harvest area/felling site directly. Therefore, these two operations, winching and skidding, are conducted with different systems, machineries and workers. Fortunately, in recent years the development of new technology in forestry mechanization created an alternative operation to ground-based systems with the use of a combi-forwarder for wood forwarding. These innovative machines allow workers to pull the logs from the stump, with a winch (installed at the rear or front of the machine) and then load and unload the platform of the combi-forwarder with the built-in crane. The interest for this combi-forwarders can be explained by the fact that it can operate as both a skidder and a forwarder, thus highly increasing the flexibility of the operator (Schweier and Ludowicy 2020). In Central European countries, combi–forwarders, i.e. forwarders with a built-in single- or double-drum winch, are spreading, but at the moment there are no published papers regarding their productivity potential and the factors that influence their performance. The aim of this research was to carry out early studies of the factors affecting the productivity of combi–forwarders in deciduous forests. The study objectives were to: (*i*) Analize the operational time consumption of the combi–forwarder with a built-in single-drum winch; (*ii*) Estimate the productivity in relation to common factors in harvesting operations; (*iii*) Determine the operation costs for the forwarder studied.

Materials and Methods

Study Site and Work Organization

The study was conducted in Vitinya State Hunting Range, located in the Western Balkan Mountains, in Sofia Province, Bulgaria. The characteristics of the areas chosen for the study are shown in Table 1. The topographical characteristics of the two study areas are very similar, with slopes that do not substantially differ between the two sites. An articulated six-wheel-drive Timberjack-1010D forwarder, equipped with a single-drum winch, as shown in Fig. 1; Table 2, was used for the tests.

The felling and processing of the trees took place with the same chainsaw operators at both sites A and site B (Fig. 2). The timber was hauled from the cutting area by the forwarder's winch in the form of stems and logs, and the larger ones – in the form of assortments. On the road, after crosscutting, the assortments were loaded by the forwarder's hydraulic crane and transported to the landing with an uphill forwarding direction.

Productivity Study and Costs

A detailed study of times and movements was carried out to estimate the duration of the elements of the work cycle and the productivity of the combi-forwarder into account the average value of the two sites under the given conditions. A work cycle was assumed to be composed of repetitive elements (Stokes et al. 1989; Olsen et al. 1998).

Table 1 Characteristics of test sites

	Site A	Site B
Location	Subcompartment 35-b N 42°48′5.1084″; E 23°46′41.9497″	Subcompartment 35-b N 42°48'11.82"; E 23°46'8.97"
Elevation	1150 m asl	1200 m asl
Function	Old-growth forest. EUNIS habitat type 3	Old-growth forest. EUNIS habitat type 3
Species composition	European beech (*Fagus sylvatica*, L) 100%	European beech (*Fagus sylvatica*, L) 100%
Stand age	150 years	150 years
Stand type	High natural forest	High natural forest
Total area	22 ha	25 ha
Logging operation	Shelterwood cutting, removal intensity 15%	Shelterwood cutting, removal intensity 15%
Average tree height	25 m	23 m
Average DBH of tree	40 cm	42 cm
Average slope gradient	31° (60%)	35° (70%)
Growing stock	5070 m^3 (317 m^3 ha^{-1})	5070 m^3 (317 m^3 ha^{-1})
Allowable cut	563 m^3 (26 m^3 ha^{-1})	563 m^3 (26 m^3 ha^{-1})
Forwarding direction	Uphill	Uphill
Average slope gradient	6% (3.6°)	8% (4.5°)

Fig. 1 The tested Timberjack-1010D forwarder

Table 2 Technical data of Timberjack 1010D

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
Travel speeds	High: 0–22 km/h; Low: 0–8 km/h
Max. tractive effort	140 kN
Dimensions:	
Length	9050 mm
Width	2700 mm
Transport height	3700 mm
Ground clearance	605 mm
Wheel base	4800 mm
Load capacity	11,000 kg
Operating weight	12,700–13,700 kg
Wood bunk:	
Length	4550 mm
Width	2565 mm
Max. cross section	3,5 m^2
Max. load rating	10,000 kg
Crane:	CF5
Gross lifting torque	102 kNm
Winch	One-drum
Cable length	65 m
Tractive force of winch cable	50 kN

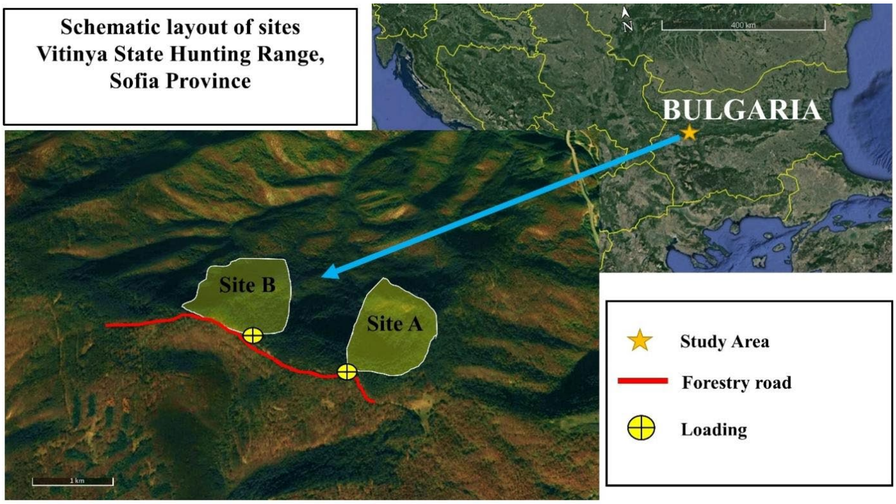

Fig. 2 Site map of the study and the schematic layout during the forwarding operations

The work cycle of of the forwarder with winch was composed of following repetitive components:

- driving empty - from landing to stand;
- maneuvering – the time for which the forwarder is as close as possible to the timber to be inhauled;
- outhaul and hook – the time for which a worker pulls the winch cable and hooks the load by chockers;
- inhaul – the time for which the logs are drawn to the forwarder with the winch cable;
- loading – the time for loading the obtained assortments on the forwarder with the hydraulic crane. When stems are pulled out, they are crosscutted during this work cycle element;
- driving loaded – the time for which the forwarder moves loaded from the stand to the landing;
- unloading – the time for which assortments are unloaded and piled in large piles on the landing by hydraulic crane;
- delays – the time for which the forwarder does not perform any work for organizational (waiting for the felling of a certain number of trees, crosscutting of the stems into assortments), technical reasons (mechanical and repair delay time), weather or terrain conditions, or the operators talking with managers or visitors.

During the study, the forwarding distance, winching distance and slope gradient, as well as the number and volume of the assortments were measured. The time-motion study was designed to evaluate the duration of work elements and productivity of the forwarder and to identify those variables that are most likely to affect it. Each work cycle was individually measured by a stopwatch. The productive time was separated from the delay time. Forwarding distance and the slope gradient of the road were measured by GPS device (Macrì et al. 2016), whereas, winching distances were measured by a professional laser range-finder with clinometer. Load volume was determined by measuring the length and the mid-length diameter of all logs from each assortment.

The machine costs were calculated using the COST model (Ackerman et al. 2014). In order to calculate the production cost for 1 m^3 timber, the cost analysis employed the following parameters: the number of operators, the hourly cost of an operator, the hourly cost of machines, the volume of extracted timber, and productive machine hours (excluding all delay times). The machine cost per hour was reported both as productive machine hours excluding delays and scheduled machine hours. The purchase prices and operator wages required by the cost calculations were obtained from accounting records (Proto et al. 2018c; Stoilov et al. 2021b). Labor cost was set to 5.60 € SMH^{-1} inclusive of indirect salary costs. Diesel fuel consumption was measured by the commonly used method of refilling to full. A salvage value of 10% of the purchase price was assumed and the Value Added Tax (VAT) was excluded.

Cost calculations were based on the assumption that companies worked for 150 working days in the year and a depreciation period of 10 years was used. For forwarding work, this amounts to 130–150 working days per year (20–21 working days per month) at an average of 6–7 scheduled working hours per day (assuming one to two hours spent on lunch, rest and other breaks). Thus yielded annual working hours were 910–1050 SMHs with a 70% use coefficient (Spinelli and Magagnotti 2011; Proto et al. 2018a).

Data Analysis

Regression analysis was performed on the l data in order to develop prediction models for estimating the work cycle time and productivity, this statistical analysis was chosen because the two study sites are very similar to each other and have no influence on the study of the work cycles, therefore the data obtained were combined. The variables used in the modelling approach included forwarding distance L, winching distance l, load volume per cycle V, slop gradient of the skidding road i, and the number of assortments in a load n. The descriptive statistics of the variables were computed and a stepwise backward regression procedure was used to model the variability of the cycle time and productivity as a function of independent variables. The confidence level used for regression analysis was 95% ($\alpha = 0.05$) and independent variables are considered significant if $p < 0.05$. To process the experimental data the Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software package was used.

Results and Discussion

Table 3 presents the mean experimental data of monitored combi-forwarder. In particular, the largest share of the working cycle elements occupies the operation "Inhaul of timber" (37% and 32% respectively, excluding and including delays), followed by the "Outhaul of line and hook" (33% and 29% respectively, excluding and including delays), travel loaded (11% and 9% respectively, excluding and including delays),

Table 3 Mean operational variables for working cycle elements

Variables	Duration, s			Distance, m		
	Mean value ± SD	min	max	Mean value±SD	min	max
Travel unloaded	378±112	139	600	802±232	270	1105
Maneuvering	120±92	20	345			
Outhaul of line and hook	1857±378	950	2680	13±5.95	0	22
Inhaul of timber	2098±500	1250	2845	13±5.95	0	22
Loading	428±226	234	1010			
Travel loaded	616±188	168	910	802±232	270	1105
Unloading	202±25	147	265			
Delays	801±231	301	1090			
Cycle time with delays	5973±1538	2384	8760			
Delay-free cycle time	5172±1381	2083	7670			
Basic descriptive statistics and performances metrics						
Number of logs per cycle	22±3.5	15	29			
Load volume, m^3	9.12±0.44	7.8	9.9			
Productivity, $m^3 \cdot PMH^{-1*}$	7.09±3.00	4.41	15.21			
Productivity, $m^3 \cdot SMH^{-1*}$	6.11±2.58	3.91	13.29			
Number of cycles per SMH*	0.67±0.29	0.41	1.51			
Mean velocity, km h^{-1}	5.83±0,45	5.03	7.07			
Mean velocity loaded, km /h-^{1}	4.78±0.56	3.76	5.80			
Mean velocity unloaded, km h^{-1}	7.62±0.93	5.55	10.41			

* SD – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour

"loading" and "travel unloaded" (both operations cover 7% and 6% respectively, excluding and including delays), "unloading" (3%), and the smallest has "maneuvering" (2%).

The breakdown by main groups of operations in delay-free cycle time shows the predominance of the winching of the load (70%), followed by the movement (18%), and loading and unloading at landing (10%).

The data from Table 3 indicate that productive time was 88% from scheduled time (Fig. 3). The delays (12%) are due to organizational reasons (delays are due to waiting for the felling of trees in the cutting area and crosscutting them into assortments at roadside) (7%), mechanical delays (1%), and those due to adverse weather conditions (rain, snow, thick fog) (2%).

The operations of pulling the winch cable, hooking the chockers, inhaul the logs and loading the assortments obtained after crosscutting occupy 77% and 68% of the duration of the work cycle without and with delays, respectively. This is due to the difficult terrain of the stand and the long and massive beech stems, which were inhauled to the machine by the winch. If the unloading time is added, then the winching operations, loading and unloading operations reach 80% and 71% of the work cycle timewithout and with delays. The mean duration of the work cycle is 86.20 and 99.55 min (1 h 26 min and 1 h 40 min), respectively, excluding and including delays, which leads to 0.41–1.51 (average 0.60) turns per hour and an average machine utilization ratio of 0.88.

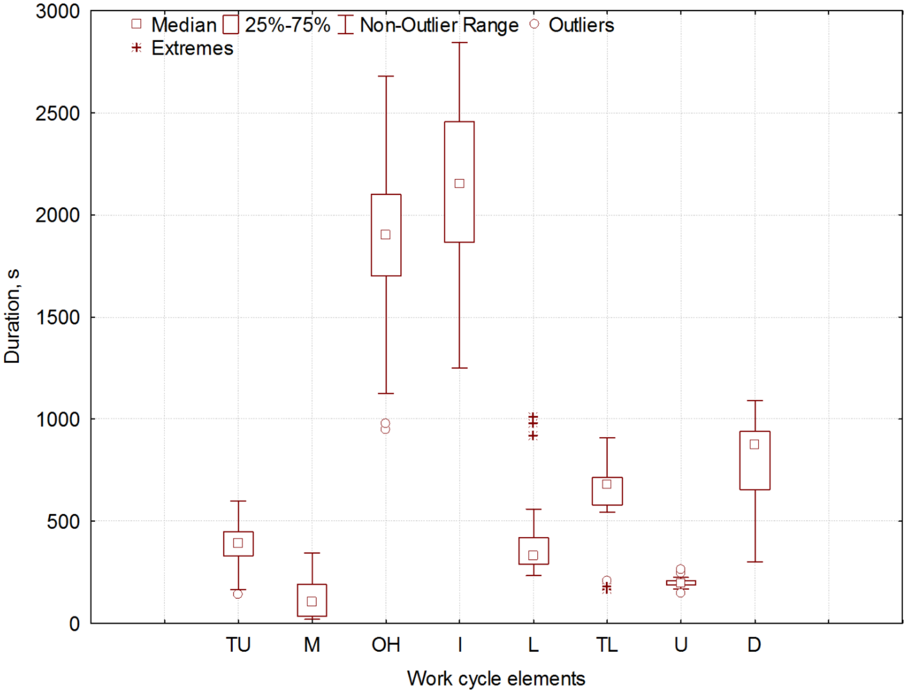

Fig. 3 Summary statistics of the work elemental time consumption (TU: Travel unloaded; M: Maneuvering; OH: Outhaul of line and hook; I: Inhaul of timber; L: Loading; TL: Travel loaded; U: Unloading; D: Delays)

Table 4 Summary of the work cycle time models

Equations	F	R^2	R^2_{adj}	Std. Error	p-Value
$T_{net} = 3.362 \cdot l$, min (1)	46.61	0.77	0.76	11.28	$p < 0.05$
$T = 3.871 \cdot l$, min (2)	61.61	0.82	0.80	11.25	$p < 0.05$

The total movement time of the combi-forwarder has a share of only 20% and 17% of the duration of the working cycle (turn) without and with delays, respectively. The forwarding distance varies widely between 270 and 1100 m, with an average of 803 m (Fig. 3). The regression analysis was done on the time-study data in order to develop prediction equations for estimating the combi-forwarder cycle time by excluding and including delays (Table 4). The delay-free cycle time T_{net} regression equation obtained with significant variables given in Eq. (1) is shown in Table 4.

In Eq. (1), the minimum duration of delay-free cycle time T_{net} can be achieved in cases of short winching distances. The regression Eq. (2) for studied combi-forwarder cycle time including delays T is also presented in Table 4. Hence, combi-forwarder cycle time including delays also depends only on winching distance l and its minimum duration may be attaining by minimizing the timber extraction distance.

Travel Speed and Inhaul Speed

The mean travel speed during the skidding phase was 5.83 km h^{-1}. The mean speeds with and without load were 4.78 km h^{-1} and 7.62 km h^{-1} respectively. The difference is almost 3 km h^{-1}, due to loaded movement was downhill, and movement unloaded was uphill with acting grade resistance. Due to the load being entirely on the forwarder, the speed is higher; in fact, Orlovsky et al. (2020) reported mean travel speed of four studied LKT 81T wheel cable skidders of 3.97 km h^{-1} (1.87–4.35 km h^{-1} unloaded and 2.56–4.05 km h^{-1} loaded). Spinelli and Magagnotti (2012) reported empty and driving loaded velocities of a 96 kW agricultural tractor of 8.1 and 7.3 km h^{-1}, respectively, which were higher than those determined in this study. The mean inhaul speed of winching of stems was 0.01 m·s^{-1} (0.36 km h^{-1}).

Productivity Analysis

Delay-free productivity was defined by the regression Eq. (3) shown in Table 5. From Eq. (3), to enhance delay-free productivity of the studied machine, winching distance *l* should be reduced.

The combi-forwarder productivity including delays is expressed by Eq. (4) also shown in Table 5. From Eq. (4), to increase productivity including delays again winching distance should be reduced, whereas the load volume per cycle *V* and forwarding distance *L* are found to be insignificant variables.

In Eqs. (3) and (4), as well as in Eqs. (1) and (2), a significant influencing factor is the winching distance because winching operations occupy a leading share of the work cycle. The mean productivity was obtained at mean a timber extraction distance of 802 m, a mean winching distance of 13 m, a mean load volume of 9.12 m^3 and a mean of 22 logs per cycle (turn) is 7.09 m^3 PMH^{-1} and 6.11 m^3 SMH^{-1}, respectively. For LKT 81T and LKT 81 ILT cable skidders, the latter with a knuckle-boom, operated mostly in beech, beech-fir and beech-oak stands, at mean skidding distance of 300 and 316 m respectively, reported lower performance: mean load volumes of 5.45 m^3 and 8.01 m^3, and gross production rates of 3.91 m^3 and 4.21 m^3 SMH^{-1}, respectively (Orlovský et al. 2020). Öztürk (2010a) found that hourly productivity of an MB Trac 900 tractor in beech stands in Black sea region of Turkey were 14.4 m^3 h^{-1} for a timber extraction distance of 55 m and 8.7 m^3 h^{-1} for a timber extraction distance of 105 m, and 11.35 m^3 h^{-1} for a timber extraction distance of 140 m and 7.70 m^3 h^{-1} for a New Holland TD85D. Borz et al. (2015) reported for an TAF 690 OP (shorter winching distance of 8.7 m, two times longer skidding distance of 1706 m, a lower load volume of 4.89 m^3 and 6.48 logs per turn) the net and gross production rates were around three time lower (4.41 m^3 h^{-1} and 3.12 m^3 h^{-1}, respectively). Due to the lack of studies in deciduous forests, the authors compared the productivity of forwarders in coniferous forests. In comparison for the John Deere 1010 forwarder

Table 5 Summary of the productivity models

Equations	F	R^2	R^2_{adj}	Std. Error	p-Value
$P_{PMH} = 15.44–0.46 \cdot l$, $m^3 \cdot h^{-1}$ (3)	58.59	0.81	0.80	1.35	$p < 0.05$
$P_{SMH} = 13.20–0.40 \cdot l$, $m^3 \cdot h^{-1}$ (4)	64.04	0.82	0.81	1.11	$p < 0.05$

deployed in coniferous stands and a mean forwarding distance 321 m, Dvořák et al. (2021) reported close mean hourly productivity ranged from 7.4 to 10.3 m^3 per machine hour; Borz et al. (2021) evaluated an HSM 208 F 14-tone forwarder under conditions of steep-terrain dominated by Norway spruce stand and found for an average forwarding distance of about 1.5 km, net productivity and efficiency rates at 14.4 $m^3 h^{-1}$ and 0.07 h m^{-3}, respectively. Proto et al. (2018b) found productivities of 14.4 and 15.7 $m^3 h^{-1}$ for forwarding distances of approximately 300 and 600 m, respectively, for two John Deere 1110D and 1010D models, operating on slopes of 26 and 29%, respectively. For steep terrain and similar timber extraction distance, Dinev et al. (2015) found productivities of 44 – 53 m^3 per day (5–6 $m^3 h^{-1}$ assuming a work shift of 8 h). Ghaffarian et al. (2007) reported an average forwarding production of about 17.9 $m^3 PSH_0^{-1}$ with mean load per trip of 10.04 m^3 and average forwarding distance of 97 m.

Therefore, the studied combi-forwarder, unifying skidding and forwarding functions, demonstrates significant efficiency in respect of the productivity in shelterwood cutting in beech stands with a removal intensity of 15%.

Cost Analysis

The hourly costs of the studied combi – forwarder, as well as the labor costs, are summarized in Table 6. As shown, the net costs for uphill forwarding were estimated at 25.33 € PMH^{-1} (productive machine hour). In the structure of the gross costs, the fixed costs (8%) were considerably lower than the labor (22%) and variable costs (70%). For the productive time of the machine, the net forwarding costs were estimated at 4.13 € m^{-3}.

For comparison, the results reported by Dvořák et al. (2021) for Czech forwarders in coniferous forests were personnel costs (35 to 66% of the total costs), followed by materials (14.9–27.1%), amortization (12.5–15.7%), and services (3.3–22.1%). The corresponding machine productivity was between 3.5 and 12.3 $m^3 SMH^{-1}$. Also in Czech Republic, in clear-felling operations in coniferous forests, Jiroušek et al. (2007) found total machine costs of 63.82 € PMH^{-1} for forwarders of a class similar to that of the studied combi-forwarder.

Table 6 Forwarding costs

Classification of Costs	Costs per hour, € h^{-1}
Total fixed costs:	1.97
Depreciation	1.93
Insurance	0.03
Taxes	0.02
Total variable costs:	**17.75**
Fuel and lubricants	8.59
Tyres	4.74
Maintenance and Repair	2.91
Winch cables and choker cables	0.30
Labor Costs	**5.60**
Net costs	**25.33**
Net costs per m^3	**4.13**

In the study in beech stands in the Black sea region of Turkey mentioned above, the cost of skidding for a MB Trac 900 tractor were 3.5 and 8.92 €·m^{-3} at timber extraction distance ranges between 55 and 105 m and average load volume for every cycle was found to be 1.49 and 2.13 m^3, respectively (Öztürk 2010a). The cost for a New Hollad TD85D in the same region for longer timber extraction distances between 140 and 320 m were 4.5 \$ m^{-3} and 8.6 \$ m^{-3} respectively (Öztürk 2010b). The costs of C Holder 870 F tractor during thinning of beech stands were ranges from 69.16 kn m^{-3} (approx. 9.19 €·m^{-3}) for a timber extraction distance of 25 m to 106.66 kn m^{-3} (approx. 14.17 € m^{-3}) for a timber extraction distance of 250 m (Zečić et al. 2005).

Proto et al. (2018b) found that the forwarding costs of a John Deere 1110D and John Deere 1010D were 3.40 €·m^{-3} in a Calabrian pine stand and 4.50 € m^{-3} in a silver fir stand in the Calabria Region (Italy). The calculated unit cost of forwarder extraction in a selective harvest in Calabria, Italy (with a John Deere 1110E), in a clear-cut on the West Coast of New Zealand (with a John Deere 1910E) and in a larger clear-cut operation in Canterbury, New Zealand (with two John Deere 1910E), forwarders ranged from 2.55 to 4.70 €·m^{-3} (Proto et al. 2018a).

In Czech Republic, Dvořák et al. (2021) monitored forwarders LVS 5, John Deere 1010, and John Deere 1110E forwarders in coniferous forest stands with a mean stem volume between 0.10 and 0.84 m^3 and forwarding distance between 261 and 560 m, the costs obtained were between 20.95 and 84.39 € PMH^{-1}. Consequently, the mentioned data show that the studied combi-forwarder, compared to other ground-based machines, is advantageous in terms of unit costs of forwarding operations in low-intensity shelterwood cuttings in beech stands.

Conclusions

In recent years, severe labor shortages have led foresters to use modern, specialized machines to compensate. Combi-forwarders combine equipment typical of skidders with that of forwarders and represent a competitive machine for improving the mechanization of winching logs and assortments, loading the received assortments, transporting them to the landing for sorting and piling phases. The data provided show a clear opportunity to promote this machine during forest operations. The combi–forwarder provides high productivity and cost efficiency compared to many ground-based machines, which makes it very suitable for logging operations in deciduous forests in mountainous conditions. The results obtained from this case study can contribute to the scientific debate and improve knowledge on forestry machinery innovation and at the same help improve the scientific database in mechanized harvesting forestry operations. Over time, further scientific studies of this machine can positively contribute to the practical management of forest planning, logging operation and, consequently, the achievement of a wider cost competitiveness of the wood supply chain.

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Declarations

Conflict of interest The authors declare no conflict of interest.

References

Ackerman P, Belbo H, Eliasson L, de Jong A, Lazdiņš A, Lyons J (2014) The COST model for calculation of forest operations costs. Int J for Eng 25(1):75–81

Apăfăian AI, Proto AR, Borz SA (2017) Performance of a mid-sized harvester-forwarder system in integrated har-vesting of sawmill, pulpwood and firewood. Ann for Res 60(2):227–241. https://doi.org/10.15287/afr.2017.909

Bettinger and Kellogg (1993) Residual stand damage from cut-to-length thinning of second-growth timber in the Cascade range of western Oregon. For Prod J 47:59–64

Borz SA, Ignea G, Popa B, Spârchez G, Iordache E (2015) Estimating time consumption and productivity of roundwood skidding in group shelterwood system–a case study in a broadleaved mixed stand located in reduced accessibility conditions. Croatian J for Engineering: J Theory Application Forestry Eng 36(1):137–146

Borz SA, Rommel D, Ziesak M, Vasiliauskas G (2019) Operational requirements and preferences towards forward-ing technology. Bulletin of the Transilvania University of Brașov – Series II: Forestry – Wood industry –. Agricultural Food Engineering 12(61):1: 1–12. https://doi.org/10.31926/but.fwiafe.2019.12.61.1.1

Borz SA, Marcu MV, Cataldo MF (2021) Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. Croatian J for Engineering: J Theory Application Forestry Eng 42(2):185–200

Borz SA, Craciun BC, Marcu MV, Iordache E, Proto AR (2023) Could timber winching operations be cleaner? An evaluation of two options in terms of residual stand damage, soil disturbance and operational efficiency. Eur J for Res. https://doi.org/10.1007/s10342-023-01536-1

Cadei A, Mologni O, Röser D, Cavalli R, Grigolato S (2020) Forwarder productivity in salvage logging operations in difficult terrain. Forests 11(3):341

Cataldo MF, Marcu MV, Iordache E, Zimbalatti G, Proto AR, Borz SA (2022) Performance of forwarding operations in biomass recovery from apple orchards. Small-scale Forestry DOI. https://doi.org/10.1007/s11842-022-09500-4

Deconchat M (2001) Effects of logging techniques on the soil surface. Annals of Forest Sciences 58:653–661

Dinev D, Vardunski J, Nacheva-Georgieva P (2015) Logging and transportation by John Deere 1110D forwarder in Bulgaria - productivity and impact on soil. In Proceedings of the 48th Symposium on Forest Mechanization, Linz, Austria, 2015, pp.373–380. ISBN: 9783900932299

Dvořák J, Jankovský M, Chytrý M, Nuhlíček O, Natov P, Kormanek M, Löwe R (2021) Operational Costs of Mid-Performance Forwarders in Czech Forest Bioeconomy. Forests. 2021, 12(4):435. https://doi.org/10.3390/f12040435

Ghaffarian MR, Stampfer K, Sessions J (2007) Forwarding productivity in Southern Austria. Croatian J for Eng 28(2):169–175

Gondard H, Romane F, Aronson J, Shater Z (2003) Impact of soil surface disturbances on functional group diversity after clear-cutting in Aleppo pine (*Pinus halepensis*) forests in southern France. For Ecol Manag 180:165–174

Holzleitner F, Stampfer K, Visser R (2011) Utilization Rates and Cost Factorsin Timber Harvesting Based on Long-termMachine Data. Croatian journal of forest engineering, 32(2011)2: 501–508

ISO (2009) Machinery for forestry—mobile and self-pro-pelled machinery—terms, definitions and classification (ISO 6814:2009). Machinery, pp 1–7

Jiroušek R, Klvač R, Skoupý A (2007) Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. J for Sci 53:476–482. https://doi.org/10.17221/2088-JFS

Karjalainen T, Zimmer B, Berg S, Welling J, Schwaiger H, Finér L, Cortijo P (2001) Energy, carbon and other material flowsin the Life Cycle Assessment of forestry and forest products. Achievements of the Working Group 1 of the COST action E9. European Forest Institute, Finland, p 68

Lindroos O, La Hera P, Häggström C (2017) Drivers of advances in mechanized timber harvesting–a selective review of technological innovation. Croatian J for Engineering: J Theory Application Forestry Eng 38(2):243–258

Macrì G, Russo D, Zimbalatti G, Proto AR (2016) Measuring the mobility parameters of tree-length forwarding systems using GPS technology in the Southern Italy forestry. Agron Res 14(3):836–845

Manner J, Nordfjell T, Lindroos O (2013) Effects of the number of assortments and log concentration on time consumption for forwarding. Silva Fennica vol 47(4):1–19. https://doi.org/10.14214/sf.1030

Mologni O, Lyons CK, Zambon G, Proto AR, Zimbalatti G, Cavalli R, Grigolato S (2019) Skyline tensile force monitoring of mobile tower yarders operating in the italian Alps. Eur J for Res 138:847–862

Nurminen T, Korpunen H, Uusitalo J (2006) Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica 40(2):335–363

Olsen ED, Hossain MM, Miller ME (1998) Statistical comparison of methods used in harvesting work studies. Corvallis O.R.: College of Forestry, Forest Research Laboratory, Oregon State University. 45 p

Orlovský L, Messingerová V, Danihelová Z (2020) Analysis of the time efficiency of skidding technology based on the skidders. Cent Eur Forestry J 66(3):177–187

Öztürk T (2010a) Productivity of MB Trac 900 tractor at beech stands on mountainous areas in Black sea region. Afr J Agric Res 5(1):028–033 ISSN 1991-637X

Öztürk T (2010b) Productivity of New Holland farm tractor at beech stands on mountainous areas in Black Sea region. For Ideas 16(139):52–56. ISSN 1314–3905 (print), ISSN 2603–2996 (online)

Pandur Z, Vusić D, Papa I (2009) Additional equipment for increasing forwarder productivity. Nova Mehanizacija Å Umarstva 30:19–25

Papandrea SF, Stoilov S, Angelov G, Panicharova T, Mederski PS, Proto AR (2023) Modeling productivity and estimating costs of processor tower yarder in shelterwood cutting of pine stand. Forests 14:195. https://doi.org/10.3390/f14020195

Picchio R, Latterini F, Mederski PS, Tocci D, Venanzi R, Stefanoni W, Pari L (2020) Applications of GIS-Based Software to improve the sustainability of a Forwarding Operation in Central Italy. Sustainability 12(14):5716. https://doi.org/10.3390/su12145716

Prem J, Bauer H (2020) Holzeinschlagsmeldung über das Kalenderjahr 2019. Bundesministerium für Landwirtschaft, Regionen und Tourismus, Wien, p 13

Proto AR, Macrì G, Visser R, Harrill H, Russo D, Zimbalatti G (2018a) Factors affecting forwarder productivity. Eur J for Res 137:143–151

Proto AR, Macrì G, Visser R et al (2018b) A case study on the productivity of forwarder extraction in small-scale southern italian forests. Small-scale Forestry 17:71–87. https://doi.org/10.1007/s11842-017-9376-z
Proto AR, Macrì G, Visser R, Russo D, Zimbalatti G (2018c) Comparison of timber extraction productivity between winch and grapple skidding: a case study in southern italian forests. Forests 2018, 9 (2), 61: 3–12
Schweier J, Ludowicy C (2020) Comparison of a cable-based and a ground-based system in flat and soil-sensitive area: a case study from Southern Baden in Germany. Forests 11(6):611
Sever S (1988) Proizvodnost i perfomanse forvardera u radovima privlacenja drva. Mehanizacija Sumarstva 18(5–6):59–87
Slugeň J, Stoilov S (2009) Productivity and time consumption of cut-to-length technology on steep terrains. In: Proc. of Scientific and technical conference "Innovations in forest industry and engineering design", 06-08.11.2009, Yundola, Bulgaria, pp. 29–35. ISSN 1314–6149
Spinelli R, Magagnotti N (2011) The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the italian Alps. For Policy Econ 13(7):520–524. https://doi.org/10.1016/j.forpol.2011.06.009
Spinelli R, Magagnotti N (2012) Wood extraction with farm tractor and sulky: estimating productivity; cost and energy consumption. Small-Scale Forestry 11: 73–85. Available at: https://doi.org/10.1007/s11842-011-9169-8
Spinelli R, Owende PMO, Ward S (2002) Productivity and cost of CTL harvesting of Eucalyptus globulus stands using excavator-based harvesters. For Prod J 52:67–77
Spinelli R, Owende P, Ward S, Torneo M (2003) Comparison of short-wood forwarding systems used in Iberia. Silva Fennica 38(1):85–94
Spinelli R, Lombardini C, Magagnotti N (2014) The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations. Silva Fennica 48(1):1003
Stampfer K (1999) Influence of terrain conditions and thinning regimes on productivity of a track-based steep slope harvester. In: Sessions, Chung (eds) Proceedings of the international mountain logging and 10th Pacific northwest skyline symposium. March 28–April 1, 1999, Corvallis, Oregon, pp 78–87
Stankić I, Poršinsky T, Tomašić Ž, Tonković I, Frntić M (2012) Productivity models for operational planning of timber forwarding in Croatia. Croatian J for Engineering: J Theory Application Forestry Eng 33(1):61–78
Stoilov S (2021a) Logging equipment in Bulgaria – current state and future prospective. Forestry Ideas, vol. 27, No 1 (61): 19–28. ISSN 1314–3905 (print), ISSN 2603–2996 (online)
Stoilov S, Proto AR, Angelov G, Papandrea SF, Borz SA (2021b) Evaluation of Salvage Logging Productivity and costs in sensitive forests of Bulgaria. Forests 12:309
Stokes BJ, Ashmore C, Rawlins CL, Sirois DL (1989) Glossary of terms used in timber harvesting and forest engineering. General Technical Report SO – 73. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 33 p
Tiernan D, Zeleke G, Owende PMO, Kanali CL, Lyons J, Ward SM (2004) Effect of working conditions on forwarder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. Biosyst Eng 87(2):167–177. https://doi.org/10.1016/j.biosystemseng.2003.11.009
Zečić Z, Krpan APB, Vukušić S (2005) Productivity of C holder 870F tractor with double drum winch Ingland 4002 in thinning beech stands. Croatian J for Eng 26(2):49–57

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