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Productivity and costs of a tracked excavator-based processor at the cable yarder landing in the North-western Italian Alps

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ABSTRACT

Excavator-based processors are a valuable machine to process trees at cable yarder landings. This paper contributes to the studies on productivity and time consumption of excavator-based processors at a landing in the North-western Italian Alps. The study analyzed the time consumption and productivity of an excavator-based processor in a spruce forest, focusing on operational factors influencing processing time and employing statistical modeling. Results showed that processing (21%) and stacking (19%) accounted for a significant portion of the total cycle time (254.2 s), with delays (48%) dominating due to waiting times for incoming loads. Regression analysis revealed that tree diameter, height, and number of logs significantly influenced cycle time. Productivity (25.7 m^3 PMH^{-1}) increased with tree volume, although larger trees required longer cycle times. Obtaining two logs per tree, when the tree volume increased by 0.1 m^3, productivity increased by about 2.5 m^3 PMH^{-1}, while when obtaining five logs per tree, the increment in productivity for the same increase in tree volume was about 1.6 m^3 PMH^{-1}. Overall, the study demonstrates the feasibility and efficiency of using excavator-based processors in forest operations in the Northwestern Italian Alps. The findings provide valuable insights into operational dynamics and economic considerations, highlighting the potential of this equipment as a cost-effective alternative.

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Performance; cycle time; modeling; time consumption; logging

Introduction

In Italy, about 45% of the forests are characterized by slopes steeper than 41%. The Alpine Regions have a steeper terrain than the national average (Gasparini et al. 2022). Mountain forests provide a wide variety of ecosystem services, which include protection against rockfall and avalanches, wildlife habitat, scenic beauty, high quality drinking water, timber harvest and carbon sequestration (Dorren et al. 2004; Forest Europe 2020). To efficiently harvest trees from challenging terrain, the use of cable yarders has emerged as an optimal solution. Cable yarders are specifically designed to facilitate tree extraction from sites with difficult access, such as steep slopes, rough terrain, and poor bearing capacity, making them particularly well-suited for mountain logging (Bont and Heinimann 2012). In fact, cable-based timber extraction and cable-assist systems are necessary for slope gradients from 20% to 40% (Davis and Reisinger 1990; Visser and Stampfer 2015). Increasingly, cable yarding systems are being considered an alternative to conventional fully mechanized systems with harvesters and forwarders due to their lower impact on soil and reduced dependency on slope gradient (Mologni et al. 2019; Erber and Spinelli 2020; Picchio et al. 2020; Papandrea et al. 2023). Additionally, in environmentally-sensitive areas the added cost of environmental compliance makes cable yarding more attractive than ground-based harvesting, even where the latter would be technically feasible (Huyler and LeDoux 1995). Alternatively, cable-assist systems have been proposed to enable ground-based machinery to negotiate steep terrain (Visser and Stampfer 2015). However, while these machines can operate on slopes of up to 105% (Holzleitner et al. 2018), they require an extensive network of skidding trails and cause significantly higher site impact compared to cable yarder extraction systems (Spinelli et al. 2010).

The Full Tree System (FTS) has become a valid option for the production of structural wood and it allows the accumulation on the landing site of residues (branches and tops) that can be chipped. This method also serves as an effective fire prevention measure by removing branch wood. On the other hand, these methods have negative effects on soil properties due to a loss of nutrients due to the extraction of residues (Achat et al. 2015). However, forest logging companies must make substantial mechanization investments to adopt FTS, making it primarily utilized in final cuts. Ensuring safety within operational conditions involve not only setting proper cutoff thresholds for load mass but also entails the correct setup and maintenance of equipment. For instance, ensuring the skyline is appropriately configured and well-maintained, including lubrication and corrosion control plays a critical role in preventing safety risks (Picchio et al. 2020). Incorporating FTS into highly productive harvesting operations on steep terrain using cable yarders entails combining delimbing and crosscutting operations at the landing using a processor head (Spinelli et al. 2022). This approach significantly boosts productivity of about 40% (Heinimann et al. 2001), reduces costs (Borz et al. 2023), lessens operator workload, and enhances safety by minimizing chainsaw use to felling operations. Processors do not create

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damage to the wooded area as they are limited to the forest roads and the landings of the cable yarders. The machines that can be employed as processors at the landing are processor tower yarders (PTY), harvesters, or general purpose-built machines equipped with a harvester or processor head, like excavators. However, a PTY has both a yarder and a processor mounted on a single carrier (Papandrea et al. 2023). The carrier is a truck, so it is limited by the conditions of the forestry road to reach the landing (slope, bearing capacity, width). Moreover, during work at the landing, the PTY cannot move from its position because it serves as the anchor point for the yarder. On the other hand, excavators and purpose-built harvesters can move from their positions, even if the presence of an additional machine could lead to an increase in costs. The excavators can rotate their booms 360°, while the purpose-built machines can rotate their booms 280°. Purpose-built machines and excavators are less influenced by the characteristic of the forestry roads. Excavators can be the ideal solution because they are very versatile machines (Wang and Haarlaa 2002) since they can be employed in various applications, including drainage maintenance, site preparation, and planting (Johansson 1997). Excavators can be used as forest harvesters (Wang and Haarlaa 2002; Magagnotti et al. 2017; Laitila and Väätäinen 2023), roadside processors (Magagnotti et al. 2017; Conrad and Dahlen 2019; Spinelli et al. 2022), stump harvesters (Walmsley and Godbold 2010; Angnes et al. 2021), and cable yarders (Torgersen and Lisland 2002; Talbot et al. 2015). The most common excavators used in forestry operations have a mass ranging from 13 t to 16 t, thus having small dimensions (Bergroth et al. 2006; Bertone and Manzone 2024).This adaptability makes them a valuable choice for a wide range of forestry tasks, providing efficiency and effectiveness in different scenarios (Johansson 1995). The popularity of the excavators likely stems from their ready availability worldwide, cost-effectiveness, robustness, ease of operation, and high compatibility with various sectors, including earthmoving, construction and road building (Talbot et al. 2014).

There are many studies of cable yarders regarding productivity and time consumption, but few studies about machines serving them at the landing, especially an excavator-based processor. The few studies about these machines in the Italian Alps are located in the Northeastern Italian Alps (Bogo and Cavalli 2003; Magagnotti et al. 2017; Spinelli et al. 2022).

This work aimed to analyze productivity and costs of an excavator-based processor at a landing in a coniferous forest in the Northwestern Italian Alps. Specifically, the objective was to study the influence of the main operational factors on the time consumption of excavator-based processors using a statistical modeling approach.

Materials and methods

Study site and stand

The study was carried out in Northwestern Italian Alps (45° 41'47'' N; 7°19'41'' E) between July and August 2023. It was done in a spruce stand (*Picea abies* Karst.) at an altitude between 1760 m a.s.l. and 1860 m a.s.l. The volume of the trees was estimated using equations reported by Tabacchi et al. (2011) for Italian tree species, based on specific data about tree species, diameter at breast height and total tree height (Tabacchi et al. 2011). The diameter at breast height (DBH) was determined for each tree using a conventional forest calliper with a measurement accuracy of 0.5 cm. Tree height was determined with a taper (Spinelli et al. 2019). The trees were motor-manually felled before the start of the extraction operations which was carried out with a truck mounted cable yarder and Woodliner 3000 carriage. The work system adopted was whole-tree harvesting. In the study site, there were two centralized landings that were 60 m from each other. Each landing had 2 corridors. The average skyline was 150 m length, 15 m of lateral yarding distance on slopes of about 40%. The direction of the extraction was uphill.

Machines analyzed

In the study, a tracked excavator equipped with a processor head was tested at the cable yarder landing. Specifically, this machine was coupled with the cable yarder, and served it to remove and process the extracted trees at the landing. The tracked excavator, used as a base machine, was a JCB JS 160 with a conventional tail swing and a weight of 17,200 kg. The nominal power of the engine was 97 kW, and the base machine's hydraulic oil flow and pressure were 2×164 l min^{-1} and 343 bar, respectively. The excavator was equipped with a mono boom with a reach at the ground level of 8.74 m and triple grouser tracks of 50 cm width. The machine was equipped with a Kesla 25RH-II processor head, chosen on base of the technical characteristics of the base machine. The power required by processor head used ranged between 75 kW and 100 kW. The hydraulic oil flow and pressure required are between 200 l min^{-1} and 250 l min^{-1} and between 210 bar and 240 bar, respectively. The maximum opening of the rollers was 58 cm, while the cutting capacity was 67 cm and the feed force was 24 kN. All the operators were skilled and proficient in their work. In particular, the excavator-based processor operator worked with the machine analyzed for 1000 h before the start of the trials. Moreover, they were instructed to work at their normal pace (Borz et al. 2014; Spinelli et al. 2019).

Time consumption and productivity

Following the methodology proposed by Magagnotti et al. (2012), working times were recorded at a cycle level (Magagnotti et al. 2012). Processing and stacking each load yarded was considered as a cycle. The time for each cycle was recorded using a digital stopwatch from a panoramic point not visible to the processor operator in order to avoid any influence on performance. Both productive and delay time were recorded. Delay time was separated from productive time. The cycles were split into 6 times elements (Nurminen et al. 2006 Wang and Haarlaa 2002; Kärhä et al. 2004; Laitila and Väätäinen 2013; Borz et al. 2014). In the time study the following work elements were observed:

Moving

beginan when the excavator-based processor started to move and ended when the excavator-based processor stoped moving to perform some other activity (empty processor head);

Positioning

beginan when the upper structure of the excavator-based processor started to swing and ended when the swing stoped moving to perform some other activity (empty processor head);

Processing (delimbing and cross-cutting)

beginan when the tree was grabbed and ended when all the cross-cut logs dropped onto the ground;

Stacking

beginan when the last log cross-cut dropped onto the ground and ended when all the logs were stacked;

Clearing

workplace clearing of branches and tops;

Delays

Time that was not related to effective work, in particular the waiting time of an incoming load was considered as delay. It was calculated as the difference between the total time of the cycle and the sum of the times of the different work elements (moving, positioning. . .).

The machine was evaluated during all processing operations of all yarding lines. However, to obtain data that was not influenced by the lateral yarding distance (obstacles on the ground, distance, . . .) only the logs under the skyline were considered for the time measurement. Trees below the line at a fixed distance of 6 meters were marked (felled trees). If there was no tree at the fixed distance, it was considered the tree closest to 6 meters.

Productivity was expressed in terms of volume (m^3h^{-1}). It was calculated, excluding delays, with the following equation (Equation 1) (Stoilov et al. 2021):

$$Productivity_{process} = \frac{3600 \times Volume}{Cycle_{process}} \tag{1}$$

where:

Volume: volume of the tree processed (m^3)

$Cycle_{process}$: sum of all the time elements (moving, positioning, ...) (s)

The efficiency was calculated and expressed in time necessary for each unit of volume excluding delay (PMH m^{-3}) (Stampfer et al. 2010; Borz et al. 2014; Huber and Stampfer 2015). It was calculated using the following equation (Equation 2):

$$Efficiency_{process} = \frac{Cycle_{process}}{3600 \times Volume} \tag{2}$$

where:

Volume: volume of the tree processed (m^3)

$Cycle_{process}$: sum of all the time elements (moving, positioning, ...) (s)

The trees processed were divided based on the quality in two different assortments with two different lengths: 2.3 m and 4.5 m.

Fuel consumption

Fuel consumption was determined using a "topping-off system." In this method, the fuel consumption was determined by refilling the machine after reaching the working temperature in the morning, during the lunch break and at the end of the work day. The fuel necessary to fill the tank was assumed to have been consumed in the hours between the refills, nevertheless, the fuel consumption indicators derived in this study used the total fuel consumption measured (Borz et al. 2021). Fuel consumption was expressed in liters per unit of hour worked (Manzone 2018). A glass pipe with a measurement accuracy of 0.02 l, was used to refill the tank (Manzone 2015). To be more accurate, an inclinometer was placed on the frame of the machine so that the inclination was ± 2°, both longitudinally and transversely, and the difference was not significant with a tank pipe diameter of 7.50 cm. Moreover, the tank was filled to a specific point in the tank pipe (±2 mm), marked with a specific marker, thus to avoid fuel leaks when inserting the cap and during the machine movements. To avoid any influence in fuel density the excavator tank was refilled the first time with the machine at a working temperature, and with a fuel temperature of 22°C. The fuel consumption was expressed per unit of time (l h^{-1}) and per unit of volume (l m^{-3}).

Cost

The hourly cost of the excavator-based processor was calculated following the methodology proposed by Ackerman et al. (machine rate method) (Ackerman et al. 2014). For the excavator-based processor, an annual use of 1200 h and 800 h was considered for the excavator and processor head, respectively. The purchase prices were 178,000 € for the base machine and 88,000 € for the processor head. A depreciation period of 10 years was assumed and a salvage value of 20% of the original investment was used in the evaluation. Maintenance and repair costs and insurance of the machine were calculated directly from the machine's owner. A cost of 23 € h^{-1} was assumed for manpower, including obligatory health and social insurance (Picchio et al. 2012). In addition, a cost of 1.50 € l^{-1} and 5.50 € l^{-1} was assumed for fuel and lubricant, respectively. The lubricant consumption was estimated at 1.8% of fuel consumption (Abbas and Handler 2018). Overheads and profit were calculated as 20% of the total cost (Hartsough 2003) (Table 1).

Data analysis

Data were processed using Microsoft Excel software and IBM SPSS Statistic (Version 28; Chicago, USA). A normal distribution of the data was tested using the Shapiro-Wilk test. Analysis of the variance was used to analyze the influence of co-variables and factors, including analysis of the interaction between the variables (Huber and Stampfer 2015). A regression analysis was performed on the

Table 1. Costs of the excavator-based processor analyzed.

Machine	Unit	Excavator	Processor-head
Purchase price	€	178,000	88,000
Salvage value	€	35,600	17,600
Service life	Years	10	10
Annual use	SMH	1200	800
Manpower	€ SMH^{-1}	23	–
Interest	%	5	5
Depreciation	€ $year^{-1}$	14,240	7,040
Interest	€ $year^{-1}$	8,900	4,400
Insurance	€ $year^{-1}$	150	–
Maintenance & repair	€ $year^{-1}$	1,500	1,500
Fuel	€ $year^{-1}$	29,700	–
Lubricant	€ $year^{-1}$	1,960	–
Personnel	€ $year^{-1}$	27,600	–
Overhead & profit	%	20	20
Overhead & profit	€ $year^{-1}$	16,810	2,588
Total cost	€ $year^{-1}$	100,860	15,528
Total cost	€ SMH^{-1}	84.05	19.41

experimental data to obtain a prediction model for estimating the work cycle time. In particular, a stepwise regression procedure was used to model the cycle time variability as a function of independent variables. The independent variables used in the modeling approach were number of cross-cuts, tree height and breast diameter (DBH). The confidence level used for regression analysis was 95% ($\alpha = 0.05$) and the assumed probability $p < 0.05$. Independent variables were significant at $p < 0.05$, i.e. a strong presumption against the neutral hypothesis.

The study included data for 120 cycles and covered 7 hours of valid cycle time. During this period, the selected machine processed 100 trees, totaling 104.4 cubic meters. The difference between the number of cycles and the number of trees is due to some trees having a larger volume. Specifically, these larger trees (>2 m^3) were divided for safety reasons before being loaded during the extraction operation.

Results

The average time for a cycle, excluding delay, was 131.4 s. The time required to complete a cycle for the excavator-based processor, including delays, ranged between 161.4 s and 472.4 s. The average delay time for each cycle was 124.6 s. The delays considered, were due to the cable yarder, specifically the distance between the load and unload point and the time required by the operators to hook the trees at the carriage. So, the delays considered were only logistics and not for maintenance and repairs. Among the productive time elements, processing (21%) and stacking (19%) represented the highest percentage of time (Table 2).

The processing and stacking phases accounted for 39% and 36% of the delay-free cycle time, respectively (Figure 1).

In general, the delay time increased in relation to the yarding distance of the trees, and, specifically, delays were directly proportional to the yarding distance (Figure 2).

The average diameter and height of the tree processed by the excavator-based processor were 34.7 cm and 20.7 m, respectively. The average volume of the trees processed was 1.0 m^3 and the average number of logs cross-cut by each tree was 3.2 (Table 3).

The statistical analysis resulted in the model presented in the following equation (Equation 3):

$$Cycle_{process} = -8.1893 + 2.3810DBH + 1.8789\,h + 5.6562Logs \tag{3}$$

Where:

$Cycle_{process}$: sum of all the time elements (moving, positioning, ...) (s)

DBH: diameter at breast height of the individual tree (cm)

H: height of the individual tree (m)

Logs: number of logs per individual tree (n)

Eighty-eight percent (88%) ($R^2 = 0.882$) of the total variation in time required for processing operations can be explained by the regression, i.e. through the co-variables DBH, height and logs obtained per each tree (Table 4).

The influence of DBH and H on the model (t-value equal to 11.0086 and 2.4688, respectively) was much higher than the influence of the Logs obtained for each tree (t-value equal to 1.8373). The high standard error (3.0784) indicates a higher

Table 2. Time consumption of the excavator-based processor analyzed.

Time element	Mean (s)	SD	Min (s)	Max (s)	Percent of total (%)
Moving	1.5	2.0	0.0	13.6	1
Positioning	12.5	4.2	5.4	23.3	5
Processing	52.1	19.2	24.9	97.4	21
Stacking	48.1	19.6	21.7	92.2	19
Clearing	15.3	4.0	7.6	27.2	6
Delays	124.7	28.8	28.6	377.4	48
Total cycle time	254.2	46.2	161.4	472.4	100

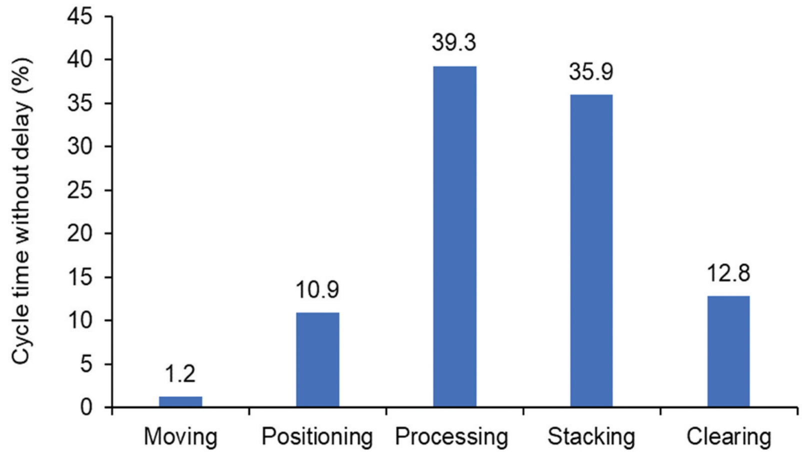

Figure 1. Percent of delay-free work cycle time by work element.

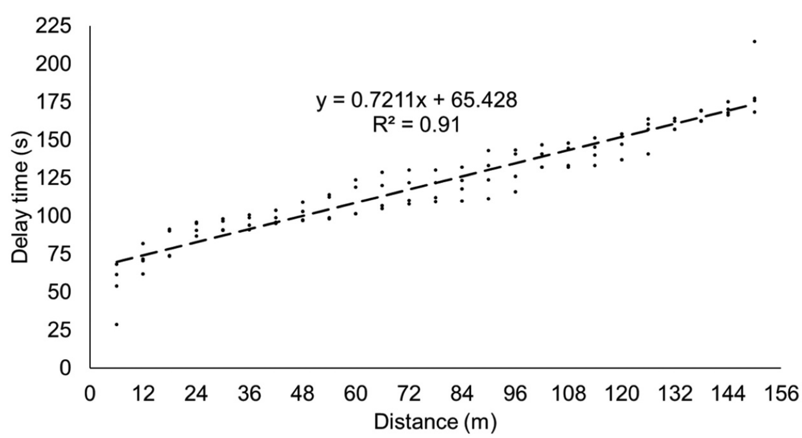

Figure 2. Relation between delays and yarding distance.

Table 3. Characteristics of the trees processed.

Parameter	Mean	SD	Min	Max
DBH (cm)	34.7	10.19	18	54
Height (m)	20.7	3.65	14	28
Volume (m3)	1.0	0.70	0.2	2.5
Logs (n.)	3.2	0.99	2	5

variability, but the confirmed significance implies that the effect of logs on time is reliable. The time required to process a single tree was directly proportional to its diameter, height and number of logs cross-cut (Figure 3).

The number of logs per individual tree generally was proportional to the height of the tree, because a taller trees makes it possible to obtain more logs. Nevertheless, the overlap between the lines is due to the possibility of obtaining a different numbers of logs depending on the quality of the wood and the presence of any defects.

The productivity calculated was 14.8 m^3SMH^{-1} and 25.9 m^3PMH^{-1}, at the given operating conditions (Figure 4).

Moreover, the productivity calculated with the cycle time obtained by the regression analysis is 25.7 m^3PMH^{-1}. The average difference between the net productivity obtained by the field data and by the regression analysis is 0.24 m^3PMH^{-1}. This difference is statistically non-significant.

The productivity of the excavator-based processor was influenced by the number of logs cross-cut within each

Table 4. Regression statistic and coefficients.

	R	R^2	Adjusted R^2	SE	P value
Regression	0.939	0.882	0.878	12.896	<0.05
Parameters	Coefficient	SE	t-stat	P value	
Intercept	−8.1893	8.9160	−0.9184	0.361	
DBH	2.3810	0.2162	11.0086	<0.05	
H	1.8789	0.7610	2.4688	<0.05	
Logs	5.6562	3.0784	1.8373	<0.05	

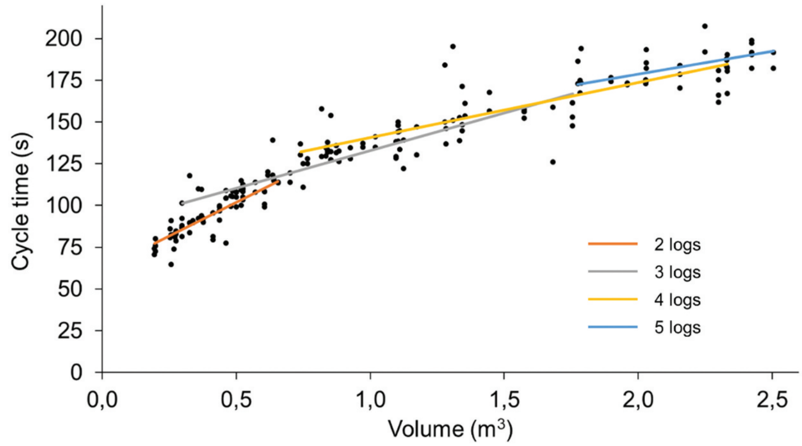

Figure 3. Cycle time of the trees processed in relation to the volume of the trees processed.

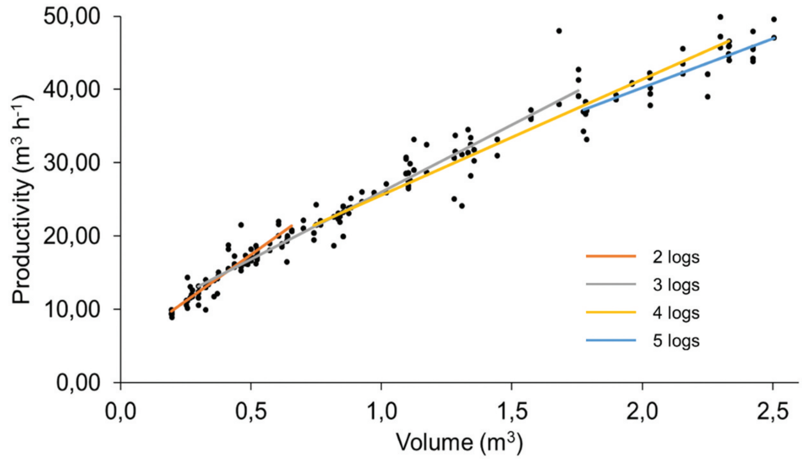

Figure 4. Productivity of the excavator-based processor per productive hour in relation to the volume of the trees processed.

tree. With high-volume trees, generally, there is an increase in the number of logs: the time needed for cross-cutting and piling increases, limiting the effect of the tree volume on productivity.

The marginal increase in productivity tends to decrease with increasing tree volume. In fact, for the first combination (2 logs), when the tree volume increases by 0.1 m^3, productivity increases by about 2.5 $m^3 PMH^{-1}$, for the fourth combination (5 logs), the increment in productivity, for the same increase in tree volume, is about 1.6 $m^3 PMH^{-1}$.

The efficiency of the entire process, expressed as the time required for processing and stacking one cubic meter of wood, ranged between 0.02 PMH m^3 and 0.11 PMH m^3 with an average efficiency across all cycles of 0.05 PMH m^3.

The total fuel consumption to complete 120 cycles was 116.2 l, equivalent to an average hourly fuel consumption of 16.5 l SMH^{-1} (Table 5).

The total hourly cost was 103.46 €, while the average cost for processing operations was 4.95 € m^{-3} (Table 1).

The cost exhibits a decreasing trend with the volume of the tree (Figure 5).

Table 5. Fuel consumption.

	Total (l)	Time (h)	Mean (l h^{-1})	Mean (l m^{-3})
Excavator based processor	116.2	7.04	16.5	1.1

However, there is an overlap between the lines in Figure 5 due to the possibility of obtaining different numbers of logs by the same volume of tree. For trees of the same volume, the cost increases directly proportional to the number of logs cross-cut from each tree.

Discussion

An excavator with a processor head working at the landing, coupled with a cable yarder used to extract the felled trees is a valuable solution to improve productivity if the alternative is motor-manual processing. However, the latter solution has a much lower productivity even if it is less expensive than excavator-based processor (Moskalik et al. 2017; Neri et al. 2023). In this case, a key factor can be safety and ergonomics for the operators. Using a regression equation for the productivity of a chainsaw in the processing phase (Vusić et al. 2012) and applying it to the data of the trees processed by the excavator, the

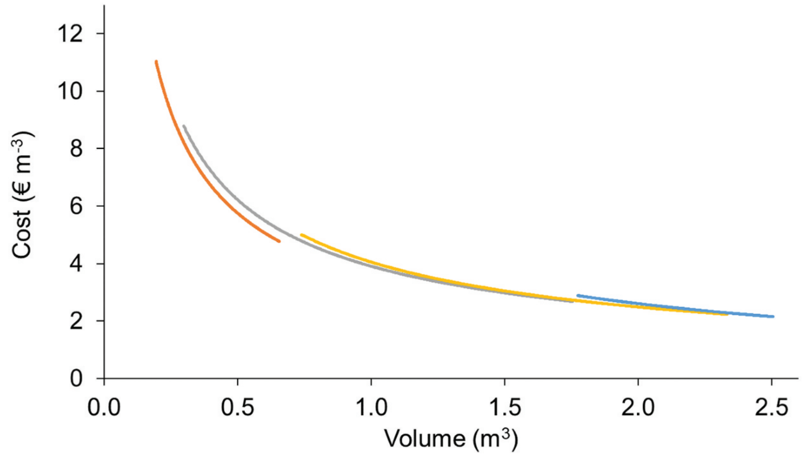

Figure 5. Cost per unit of volume for the excavator-based processor in relation to the volume of the trees processed.

productivity was 6.96 m^3/PMH. This value is 47% lower than the productivity obtained by the excavator-based processor tested.

The time consumption of the excavator-based processor is closely linked to the overall time consumption of the cable yarder, resulting in significant delays for the processor. These delays primarily stem from waiting for loads to arrive at the landing before processing operations can start. The high incidence of delay in this study underscores the logistical challenges associated with coordinating extraction and processing operations in mountainous terrain with a high correlation ($R^2 = 0.91$) between delays due to waiting for the incoming load and the yarding distance. The incidence of delay in this study (48%) is higher than in a study in which a processor works on unloading material extracted by cable skidders (21%) (Borz et al. 2023). This is caused by the lower transport capacity of the cable yarder compared to the skidder where load capacity is much higher.

The productivity obtained in this work is 60% lower than that obtained by a processor tower yarder, but this machine worked with a much higher tree volume and the cycle time was faster (Papandrea et al. 2023). The time per cycle, obtained with trees of 35 cm (DBH), height 19 m and volume equal 0.9 m^3, was 42% higher than the cycle time of the processor tower yarder (Papandrea et al. 2023). This difference is caused by the difference of the stationary conditions where data were collected (different growing stock and trees dimensions). The cycle time calculated with the regression equation in our study is 22% lower than that obtained by a regression equation obtained in a study in the Northeastern Italian Alps (Bogo and Cavalli 2003). This is due to the different volumes of the trees: it was 1.3 m^3 (Bogo and Cavalli 2003), about 33% higher than the volume of the trees processed in this study (1.0 m^3).

The productivity is in line with that obtained in the study that used a very similar excavator-based processor at a landing in the oriental Alps (Bogo and Cavalli 2003). Another solution for the use of the excavator as a base machine with high versatility is represented by the excavator-based yarder studied by Talbot et al. (2014). This machine is unique in that it is fully integrated with both yarding and processing capability (Talbot et al. 2014). The productivity of the integrated yarder processor is about 54% lower than the productivity obtained by the excavator-based processor analyzed in this work. The lower productivity is caused by the small tree volume processed (0.27 m^3 vs. 1.0 m^3). Moreover, the excavator-based yarder cannot perform both operations (yarding and processing) simultaneously (Talbot et al. 2014).

The influence of tree characteristics on processing operations time underscores the importance of considering factors such as diameter at breast height (DBH) and the number of logs per tree. Larger trees with greater diameters and more logs necessitate longer processing times, contributing to lower overall productivity. However, it is crucial to note that while larger trees may require more processing time, they also yield higher volumes of timber, which can offset productivity losses to some extent (Nakagawa et al. 2010).

The efficiency of the excavator-based machine (0.048) is in line with that obtained during processing and stacking logs at a landing by a purpose-built machine (0.047) (Borz et al. 2023). However, that machine was 50% more efficient than a processor tower yarder that worked in a spruce stand (Borz et al. 2014). But this processor tower yarder worked in a thinning operation with a smaller tree volume. This efficiency metric provides valuable insights into the operational effectiveness of the machine, offering a benchmark for evaluating its productivity relative to resource utilization.

Fuel consumption is in line with fuel consumption obtained by other excavator-based processors analyzed in other studies (Johansson 1995; Magagnotti et al. 2017). The fuel consumption was 22% lower than the fuel consumption of a purpose-built machine used at a landing to process trees (Borz et al. 2023). However, the unit fuel consumption was 42% higher than the fuel consumption of a purpose-built machine used at a landing to process trees (Borz et al. 2023) because the excavator's engine is not designed specifically for this kind of operations (Spinelli and Moura Ac de 2019).

The cost analysis demonstrates the excavator-based processor's cost-saving potential compared to purpose-built machines, particularly as tree volume increases. The declining cost trend with increasing tree volume underscores a better fuel efficiency for larger trees. The cost per unit of volume (m^3) is 4.95 €, a value 50% lower than a purpose-built machine that works for 200 days per year (Borz et al.

2023). The excavator worked with the processor head for only 100 days per year. The cost analysis demonstrates the excavator-based processor's cost-saving potential compared to purpose-built machines, particularly as tree volume increases. The declining cost trend with increasing tree volume underscores the economic advantages of scaling up operations, as higher volumes translate to lower costs per unit of wood processed (Wang and Haarlaa 2002; Laitila and Väätäinen 2013; Magagnotti et al. 2017).

Conclusions

Based on the results of this study, the time required to process at the cable yarder landing using an excavator-based processor is influenced by the DBH of the tree processed and its height. It was only minimally influenced by the number of logs obtained. However, the productivity was directly proportional to the volume of the trees as it is possible to obtain a greater number of logs with increasing tree diameter. It must be highlighted that the major influence on the increment of productivity was due to the tree size. Moreover, the excavator equipped with processor head, coupled with a cable yarder, can increase the productivity if compared with motor-manual felling. Furthermore, the use of an excavator-based processor represents a cost-saving alternative to purpose-built machines. The cost is inversely proportional to the volume of the tree processed. Further research should focus on minimizing delays and exploring advanced logistical strategies to optimize the integration of extraction and processing activities in steep terrain environments.

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No potential conflict of interest was reported by the author(s).

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