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Estimation of Productivity and Costs of Using a Track Mini-Harvester with a Stroke Head for the First Commercial Thinning of a Scots Pine Stand

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Abstract: The aim of the present work was to estimate the productivity and costs of timber harvesting and forwarding during the first commercial thinning of a Scots pine stand. Three harvesting models were introduced and compared: narrow trail, wide access trail, and schematic extraction. The analyzed harvesting equipment consisted of a track mini-excavator (34 kW) with a stroke harvester head (gripping range 4–30 cm), and a farm tractor coupled to a logging trailer with a hydraulic crane. Merchantable timber (roundwood with a minimum diameter of 5 cm inside bark) was harvested from a 25-year-old planted Scots pine stand growing on a grid of 1.4 m × 1.8 m. The study showed the productivity of the mini-harvester ranged from 3.09 to 3.47 m^3/PMH_{15} (productive machine hours plus 15 min), and that of the forwarding equipment to be 4.07 m^3/PMH_{15}. The analyzed model of productivity as a function of tree volume and thinning intensity was statistically significant, but the intensity parameter was significant only on plots located along wide access trails (3.7 m) and insignificant on plots located along narrow access trails (2.5 m). The distance between trees was not found to be significant. The calculated net machine costs for the forwarding equipment and track mini-harvester were EUR 36.12 and 52.47 per PMH, respectively. An increase in the usage rate of the harvesting equipment to 80% would reduce the harvesting and forwarding costs to EUR 22.07/m^3.

Keywords: logging; harvesting intensity; forwarding; thinning; productivity; costs

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1. Introduction

According to the State of Europe's Forests report [1], Poland has a relatively large forest area (9.4 million ha) with a growing stock density higher than the European average (269 m^3/ha). This translates into a growing stock volume of over 2.5 billion m^3, offering a vast source of wood for the region. Most of Poland's forests are publicly owned (80.8%), including forests managed by the State Forests National Forest Holding (77.0%). Among the latter, the largest area, ~4 million ha, contains stands of 20–80-year-old trees, representing almost 60% of the available wood stock. Taking into consideration different climate change scenarios [2], it is estimated that the highest productivity of Scots pine stands can be achieved with medium thinning (20–40%).

According to Karttunen et al. [3], timber in Scandinavian countries is largely harvested by thinning, which becomes increasingly relevant both to the bioenergy sector and to developing industrial investments. Considering different harvesting alternatives in in the context of the timber supply chain and stand lifecycle, the authors concluded that intensive thinning leads to lower stumpage prices, with harvesting technology having the greatest influence on silviculture productivity. They also noted that whole-tree harvesting leads to the highest biomass production, but also to lower future stumpage prices and decreased forest profitability. Furthermore, a growing body of research is taking into account the effects of forest management on ecosystem development and carbon sequestration, which is of great significance to containing climate change [4–6].

Harvesting constitutes the main and most cost-intensive element in the timber supply chain, with the costs largely dependent on thinning intensity, average tree volume, and type of equipment. Single-grip harvesters seem to be the most effective, especially in older tree stands, while bundling technology appears to be useful for small-diameter thinning as it reduces transport costs [7–9]. However, the high cost of whole-tree harvesting indicates a need to identify more effective operating procedures, such as the two-pile cutting method [3], also known as the part tree system, in which the harvested trees are separated into stump wood and energy wood.

According to the Forest Stewardship Council (FSC), one of the standard requirements following harvesting is to leave an increased amount of deadwood stock [10], which has a large impact on water status, soil conditions, and thus biodiversity and sustainable development [11,12].

Several authors pointed out that thinning young stands presents several dilemmas, including high operational costs, frequency of invasive trips involving various kinds of field machinery, tree damage [13,14], and mental stress on the harvester operator [15–17]. To improve its efficiency, new and more effective methods for harvesting are being sought [18,19].

Polish forestry has traditionally focused on natural, non-schematic, and comprehensive forest management, and silvicultural treatments have usually been carried out by means of the cheapest motor-manual equipment [13,20,21]. However, economic growth has led to a situation in which few workers are willing to engage in this kind of demanding manual labor. Hence, alternative forest technologies are being sought to address this increased deficit in labor supply and to apply more frequent but less invasive procedures.

Given current market conditions (the dominant consideration of the State Forests National Forest Holding), forest contractors predominately work on short-term contracts [22–24] and are reluctant to pursue state-of-the-art technological solutions because of the high financial risk, the financial standing of the forest districts, and seasonal competition from foreign contractors during periods of low overseas demand. These contractors usually work in agriculture and construction, but are seeking alternative uses for their equipment, so excavators are often equipped with harvester heads and tractors are coupled to logging trailers with hydraulic cranes, which compete with specialized forwarders [25–27].

The intensification of timber harvesting (e.g., via tending treatments) is motivated by, amongst other things, social expectations and environmental considerations. In recent years, a considerable body of research on renewable energy sources has shown that small-diameter (DBH < 10 cm) thinnings can be an efficient source of biomass in the form of whole trees or stems [28,29] if there is an efficient access road network [30]. In Poland, whole-tree harvesting is avoided for environmental reasons as it may adversely affect habitats [31], and merchantable timber harvesting is mostly used for commercial purposes (chemical processing or manufacture of furniture boards).

The aim of this study was to estimate the productivity and costs of harvesting timber using a tracked excavator-based harvester and forwarding the raw material with a forest trailer during the first commercial thinning on wide (3.5 m) and narrow (2.7 m) access trials. In order to determine the significant factors influencing the above-mentioned work technology efficiency parameters, it was assumed that the productivity models would be sufficiently explained by tree volume, thinning intensity and average distance between trees, and show differences in harvesting efficiency between narrow, wide and schematic tree extraction.

2. Materials and Methods

2.1. Description of the Harvesting Systems

The harvesting equipment used in this study consisted of a 34 kW Kubota KX057-4 mini-excavator with an Arbro 400 S stroke harvester head (hereinafter referred to as a "mini-harvester") and an MTZ Belarus 952.2 farm tractor coupled to an FAO FAR 842 logging trailer with a hydraulic crane (outreach of 6.4 m) (hereinafter referred to as "forwarding equipment").

In the first phase of the study, timber was harvested from the sample plots located along wide access trails (AT35). The trees to be cut were selected by foresters and clearly marked with paint at a height of approx. 1.5 m for ease of identification. They were processed into 2.5 m logs (using cut-to-length technology) with a minimum diameter of 5 cm inside the bark, and then placed along the trails. Thinning was conducted using a mini-harvester consisting of a tracked excavator with an Arbro 400 S stroke harvester head (Table 1). Due to the relatively short crane range (6.5 m), the mini-harvester had to move off the trail to perform thinning on the entire area of the designated sample plots.

Table 1. Characteristics of the timber harvesting equipment.

	Unit	Kubota KX057-4 Excavator with Arbro 400 S Harvester Head	MTZ Belarus 952.2 Farm Tractor	FAO FAR 842 Logging Trailer with 3264 Crane
Engine	kW (HP)	34 (46)	66 (90)	-
Dimensions length/height/width	mm	5520/2550/1960 Overall	4090/2840/1970 Overall	4420/1630/1250 Load compartment
Minimum ground clearance	mm	310	465	620
Operating weight	kg	5550 (excavator) 330 (harvester head)	4500	2550 (8 t load capacity)
Maximum outreach	m	6.5	-	6.4
Gripping range	mm m^2	(40, 300)	-	0.16
Maximum angle	mm	360	-	1200
Delimbing speed (backwards/forwards)	m/s mm	0.3–0.5 stroke: 660	-	-

In the second phase, narrow-access trails were made by schematic extraction of single rows of trees (AT27 schemextraction). Due to the relatively low ground clearance of the mini-harvester (310 mm, Table 1), the remaining stumps had to be removed, and the trail leveled by a mounted blade.

In the third phase, thinning was performed on the sample tree stand plots along the new narrow-access trails (AT27) using the same harvesting equipment with a crane having an outreach of 6.4 m (Table 1). The volume of the transported loads for each work cycle was calculated in cubic meters, including bark, after being unloaded at a landing area near a paved road 700 m away.

2.2. Study Description

The study was conducted in a 25-year-old Scots pine stand (50°13′43″ N; 23°12′39″ E), which was a 120 m × 240 m rectangle containing two 3.5 m wide access trails (AT35) made during planting that divide the shorter edge into three equal 40 m segments, which is typical for motor-manual harvesting. To facilitate mechanized thinning, three additional 2.7 m wide access trails (AT27) were cut parallel to the existing ones by schematically removing one tree row for each. In this way, the stand had a parallel network of trails spaced every 20 m, which allowed the hydraulic crane full access.

Due to the large number of trees to be removed (more than 1300) and for the sake of observer safety, small 25 m × 20 m sample plots were established 10 m on either side of the access trails (Figure 1). These plots were demarcated using a Ledha–Geo laser optic-system produced by Jenoptik (Jena, Germany).

The study involved the harvesting of merchantable timber (roundwood with a minimum diameter of 5 cm inside bark) from a planted Scots pine stand in which trees were grown on a 1.4 m × 1.8 m grid at the time of the tending treatment, which could be classified as the first commercial thinning. The growing stock density was approximately 175 m^3 of merchantable timber outside bark with approximately 2200 trees per ha (Table 2). A total of 50 rectangular sample plots and 15 sample segments were established along the new access trails (AT27 schemextraction).

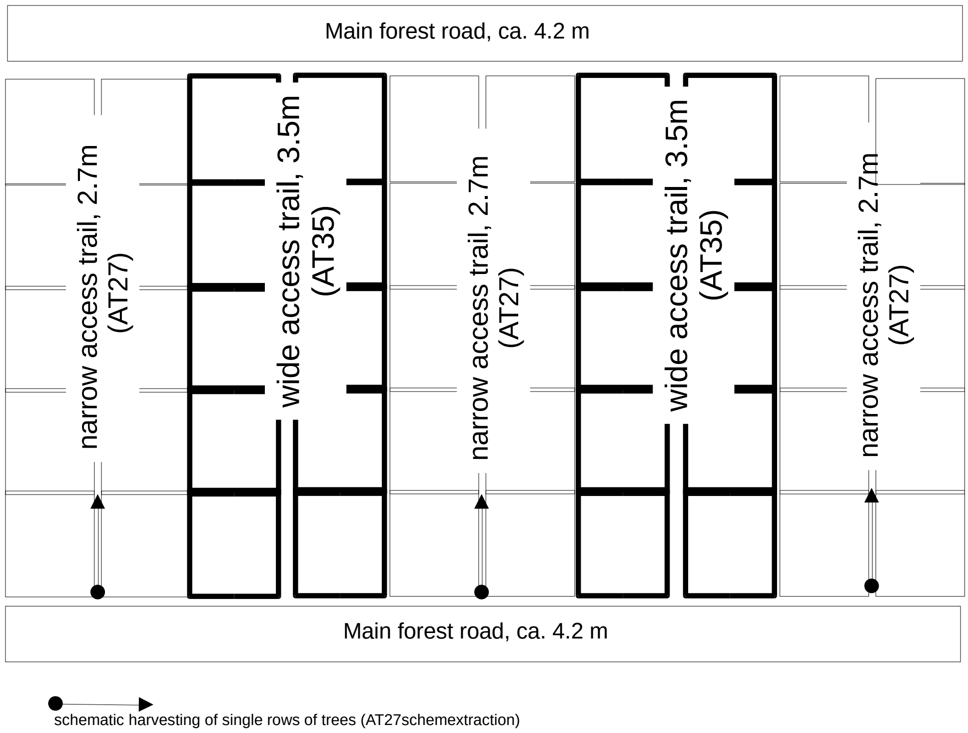

Figure 1. Scheme of sample plot location.

Table 2. Summary of stand characteristics.

Description	Unit	Sample Plots along Wide Access Trails (AT35)	Sample Plots along Narrow Access Trails (AT27)	Schematic Tree Extraction along the Rows (with Stump Removal and Level of Trail) (AT27 Schemextraction)
Area	ha	1	1.5	0.10
Average diameter at breast height (DBH) outside bark	cm	11.7	12.3	13.5
Initial tree density	number per hectare	2353	2142	1882
Average height of removed trees (dominant height of 10%)	m	13.4 (15.0)	13.4 (15.0)	13.4 (15.0)
Average tree volume (95% confidence interval)	m^3 outside bark	0.074 (0.061, 0.087)	0.082 (0.073, 0.090)	0.103 (0.095, 0.111)
Thinning intensity volume (v/v) per sample plot in percent (95% confidence interval)	%	18.8 (15.1, 22.5)	27.8 (24.2, 31.4)	100
Average relative spacing index RSI/Hart–Becking index (95% confidence interval)	m	12.15 (11.59, 12.72)	12.96 (12.27, 13.65)	12.64 (12.15, 13.12)
Number of sample plots	n	20	30	15
Tree species	-	Scots pine	Scots pine	Scots pine
Age	year	25	25	25
Stand quality [1]	-	IA	IA	IA
Stocking degree [2]	-	1.0	1.0	1.0
Forest type		Fresh mixed coniferous	Fresh mixed coniferous	Fresh mixed coniferous

[1] IA is the highest rate of habitat production capacity on six-step scale; [2] stand stocks compared to the potential habitat production (178 m^3/ha).

2.3. Productivity and Cost Analysis

To estimate machine productivity precisely, the present work focused on work time as defined in the IUFRO 1995 classification [32]: main work time (cutting, processing, loading, unloading, and turning) and complementary work time (root extraction, intertree movement, unloading, and turning). As has been mentioned by numerous authors [33,34], a 15 min rest per 8-hour shift was added to productive work time to comply with occupational safety and health standards, which meant that the resulting time was expressed as productive machine hours plus 15 min (PMH_{15}). The duration of the various work elements was measured both in harvesting and forwarding work cycles. Given the purpose of estimating the effects of tree stand characteristics (thinning intensity and tree density) on mini-harvester work time and productivity as well as other operating parameters, the variables were measured separately in cycles for each sample plot. Measurements were calculated to an accuracy of 1 s using a PSION WorkAbout data recorder with dedicated software. In summary, the observation was conducted on 65 sample plots while 1327 timber-processing work cycles were observed.

The machine costs were computed pursuant to FAO guidelines [35], and the harmonized procedure proposed by Ackerman et al. [36] used the basic data presented in Table 3. The costs were computed for the Polish market at the rate of 1 EUR = 4.23 PLN. The calculation included the costs of transport and garage, provided by an external company, and of replacing tracks and tires. Repair costs were adopted as 100% of the purchase price for the mini-harvester and the farm tractor and 60% for the logging trailer.

Table 3. Basic data used in cost calculation.

	Unit	Kubota KX057-4 Excavator with Arbro 400 S Harvester Head	MTZ Belarus 952.2 Farm Tractor	FAO FAR 842 Logging Trailer with 3264 Crane
Average fuel consumption (0.95 CI)	dm/PMH	2.2 [a] (1.4, 3.1)	8.5 [b]	
Average speed on sample plots (0.95 CI)	m/s	0.43 [c] (0.36, 0.52)	1.45 [d] (1.19, 1.72)	
Purchase price (VAT 0%)	EUR	90,000	20,000	13,800
Estimated annual productivity [e]	m^3/year	3028	4307	4307
Expected economic life [e]	year	7.68	9.45	9.45
Salvage value	%	10	10	10
Machine utilization rate [e]	%	62	63	63

[a] own data developed on 94 PMH; [b] technical data; [c] calculated from 24 measurements using Ledha–Geo; [d] calculated from 11 driving cycles; [e] preliminary calculations according to the cost model by Ackerman et al. (2014).

2.4. Statistical Analysis

Tree volume was determined indirectly based on a formula for pine stem volume inside bark [37] using parameters such as stand-specific taper factor, outside-bark diameter at 1.3 m (DBH), and tree height. DBH was determined directly by measuring all trees selected for felling by means of a digital caliper. Individual tree heights were calculated indirectly from a curve determined for the stand based on a measurement of 5% of trees using a Ledha–Geo laser dendrometer. For the purpose of calculating tree volume outside the bark in cubic meters, it was assumed that the bark accounted for 12% of the total volume [38].

Homogeneity of the designated sample plots was evaluated by calculating the thinning intensity as the volume of harvested merchantable timber relative to total merchantable timber, as well as the Hart–Becking index (or relative spacing index, *RSI*) for the dominant tree height:

$$RSI = 100 \times \frac{AS}{H_{dom}} \quad (1)$$

where AS is the average spacing between trees in meters (assuming positioning on a triangular grid) and H_{dom} is the average height of the tallest 10% [39].

Statistical analysis consisted of descriptive statistics, Fisher's F-test for equality of variances, and Student's *t*-tests for homoscedastic data (with equal variances) and non-homoscedastic data. It was assumed that the analyzed relationship would be close to exponential, so the data were transformed into natural logarithms. Among other things, it allowed for the use of a wide range of parametric statistical tests, which are useful in operational research because they involve simple transformations. The model functions were determined using the generalized linear model (GLM)

$$lnY = b_0 + b_1 \times lnX_1 + b_2 \times lnX_2 + b_3 \times lnX_3 + \varepsilon \quad (2)$$

where Y is the dependent variable (productivity); $X_{1...k}$ is the independent variable (X_1, merchantable timber volume outside bark; X_2, thinning intensity; X_3, relative spacing index RSI); and ε is the estimation error.

Due to the relatively small differences in the adopted model, the statistical significance of differences between marginal means was evaluated by contrast analysis in the form of a priori tests for selected average comparisons. Analysis of the residuals (ε) of linearized regression functions included tests for normality of distribution using the Shapiro–Wilk test, which confirmed the lack of bias and random error in the estimated models. Statistical analysis was performed using the StatSoft [40] and R Core Team [41] packages. The following power function model was applied to predict productivity in m^3/PMH_{15} by converting logarithmic values into real values):

$$Y = b_0 \times X_1^{b_1} \times X_2^{b_2} \times X_3^{b_3} \quad (3)$$

The analysis of the marginal productivity functions was performed as a simple regression coefficient analysis, separately for each associated variable (access trail, tree volume).

3. Results

The first step in the analysis involved assessing the homogeneity of sample plots established along the wide (AT35) and narrow (AT27) trails. Statistical tests (Table 4) show that neither individual tree volume nor RSI differed significantly. However, the plots along the wide access trails exhibited significantly higher RSI variance and lower thinning intensity (Δ = 8.97%).

Table 4. Homogeneity of sample plots along the wide (AT35) and narrow (AT27) access trails.

Variable	*F*-Test for Equal Variances		*t*-Test for Equal Average	
	***F*-Stat**	***p*-Value**	***t*-Stat**	***p*-Value**
Tree volume outside bark [m^3]	0.6551	0.1485	2.0106 [b]	0.3060
Relative spacing index (RSI)	2.0772	0.0339 [a]	1.7667 [c]	0.0836
Thinning intensity (volume)	1.4275	0.2112	2.0106 [b]	0.0019 [a]

[a] statistically significant at α = 0.05; [b] *t*-statistic for equal variance (homoscedasticity); [c] *t*-statistic for unequal variance (non-homoscedasticity).

As can be seen from Table 5, the mini-harvester with an Arbro 400 S head had the lowest productivity (3.09 m^3/PMH_{15}) for sample plots located along the wide access trails, while it achieved the highest productivity (3.47 m^3/PMH_{15}) for the schematic extraction of single rows. The productivity of the forwarding equipment (Belarus 952.2 farm tractor with a FAO FAR 842 logging trailer) was found to be 4.07 m^3/PMH_{15}.

Table 5. Productivity characteristics of sample plots, m^3/PMH_{15}.

Variable	Harvesting: Kubota KX057-4 with Arbro 400 S: Sample Plots along Wide Access Trails (AT35)	Harvesting: Kubota KX057-4 with Arbro 400 S: Sample Plots along Narrow Access Trails (AT27)	Harvesting: Kubota KX057-4 with Arbro 400 S: Schematic Tree Extraction along the Rows (within Stump Removal and Level of Trail), (AT27 Schemextraction)	Forwarding: MTZ Belarus 952.2 Tractor with FAO FAR 842 Trailer
Average	3.09	3.28	3.47	4.07
SD	0.93	0.71	1.81	0.66
max	5.29	5.09	6.43	5.11
min	1.26	1.46	1.07	3.03

The general results (Table 6) indicate the absence of statistically significant differences in mini-harvester productivity between sample plots along wide (AT35) and narrow access trails (AT27). Therefore, the two types of sample plots were combined with net cost and productive analyses (Table 7, Figure 2). However, a more accurate analysis of performance models showed up to 12% higher productivity on narrow trails (AT27) for the same tree volume (Table 8).

Table 6. Contrast analysis for marginal average.

Variable	Contrast 1	Contrast 2
AT27	−1	−1
AT35	1	−1
AT27 schemextraction	0	2
Contrast evaluation	−0.0158	0.3912
t-stat	−0.3781	4.5046
p-value	0.7067	3.1×10^{-5}

Table 7. Linear regression analysis of mini-harvester productivity (Equation (1)) with an Arbro 400 S head as a function of average stump volume.

Parameter	Value	Std. Error	*t*-Stat	Residual, ε (Average SD)
Model 1: Total sample plots along narrow and wide access trails (AT35 and AT27)				
b_0	3.0239	0.0893	33.846 *	(0, 0.0868) S–W = 0.9621 p = 0.1090
b_1	0.7283	0.0340	21.423 *	
Model 2: Schematic tree extraction along the rows (within stump removal and level of trail) (AT27 schemextraction)				
b_0	2.8154	0.2312	12.178 *	(0, 0.2527) S–W = 0.9472 p = 0.4811
b_1	0.7224	0.0927	7.791 *	

* statistical significance at $p < 0.001$.

Based on these data, the next step of analysis involved estimating the mini-harvester productivity function. In Model 1 (Table 7), when productivity on sample plots was characterized as a function of individual tree volume ($R^2_{adj.}$ = 0.91), the RSI effect (b_2) was not found to be statistically significant (p = 0.220); however, statistical significance was confirmed both for the intercept (b_0) and individual tree volume (b_1). In Model 2 ($R^2_{adj.}$ = 0.82), mini-harvester productivity was estimated for schematic tree row extraction during the clearance of new narrow trails and shown to be lower compared to operating on rectangular sample plots. Residual analysis indicates random distribution and absence of bias (average = 0) and random error ($p > 0.05$ for Shapiro–Wilk test). As can be seen from the functions for real values (Equation (3) and Figure 2), the decrease in productivity amounted to approx. Δ = 0.58 m^3/PMH_{15} for the adopted average outside-bark tree volume (0.08 m^3).

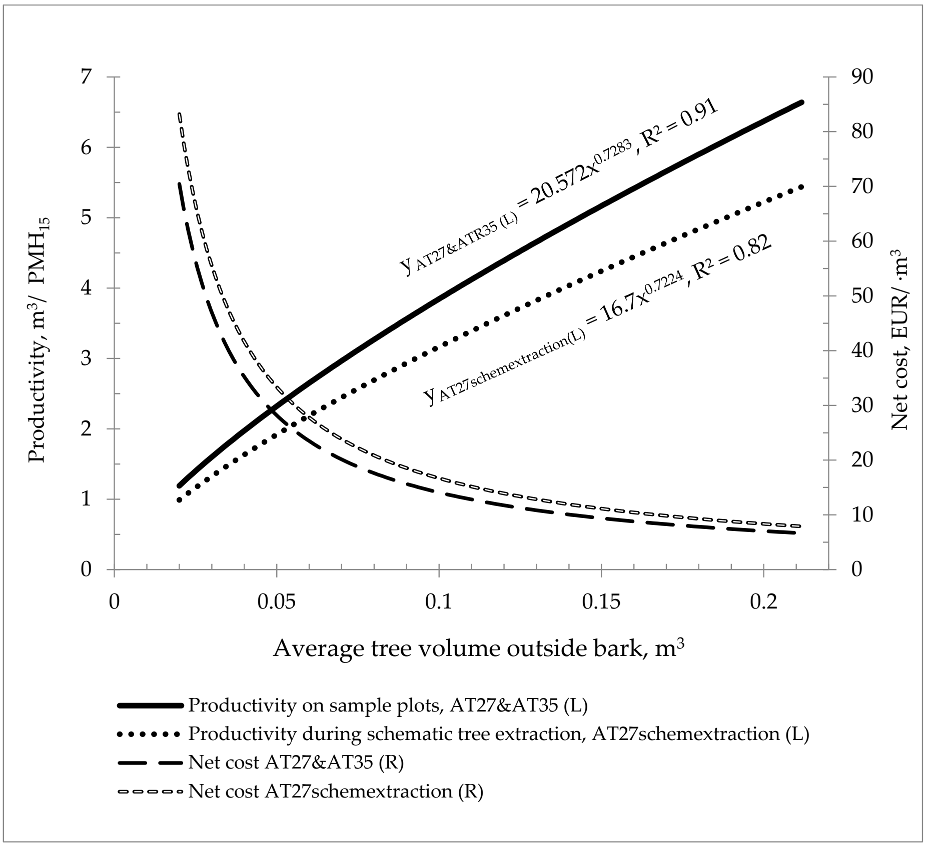

Figure 2. Productivity and net cost of using the mini-harvester with Arbro 400 S as a function of average tree volume.

Table 8. Linear regression analysis of the productivity (Equation (1)) of the mini-harvester with an Arbro 400 S head as a function of average stumpage volume (X_1) and thinning intensity (X_2).

Parameter	Value	Std. Error	*t*-Stat	Residual, ε (Aver., SD)
Model 3: Sample plots along wide access trails (AT35)				
b_0	3.0486	0.1987	15.3439 *	(0.000, 0.1189) S–W = 0.9388 p = 0.2277
b_1	0.6034	0.0830	7.2700 *	
b_2	0.2021	0.0511	3.9578 *	
Model 4: Sample plots along narrow access trails (AT27)				
b_0	3.2387	0.2941	11.0122 *	(0.000, 0.1660) S–W = 0.9508 p = 0.1779
b_1	0.8093	0.1151	7.0344 *	

* statistical significance at $p < 0.001$.

The identified differences in thinning intensity (Δ = 8.97%, Tables 2 and 3) on sample plots located along the wide and narrow access trails (AT35, AT27) were adopted as the basis for estimating further productivity functions while taking into consideration variables such as tree volume and thinning intensity (Models 3 and 4, Table 7). The obtained parameters were statistically significant for Model 3, which described productivity on sample plots along the wide access trails (AT35) with the errors being random. In Model 4, which described sample plots along the narrow access trails (AT27), thinning intensity (b_2) was not statistically significant ($p = 0.9514$).

Analysis of marginal productivity functions (Figure 3) showed higher average productivity for sample plots along the wide access trails (AT35; $R^2_{adj.} = 0.5192$, F = 8.304, $p = 0.008$) at thinning intensity greater than 23%, while at lower thinning intensity higher productivity was observed for sample plots along the narrow access trails (AT27, $R^2_{adj.}$ = 0.0291, F = 0.840, p = 0.367, not significant).

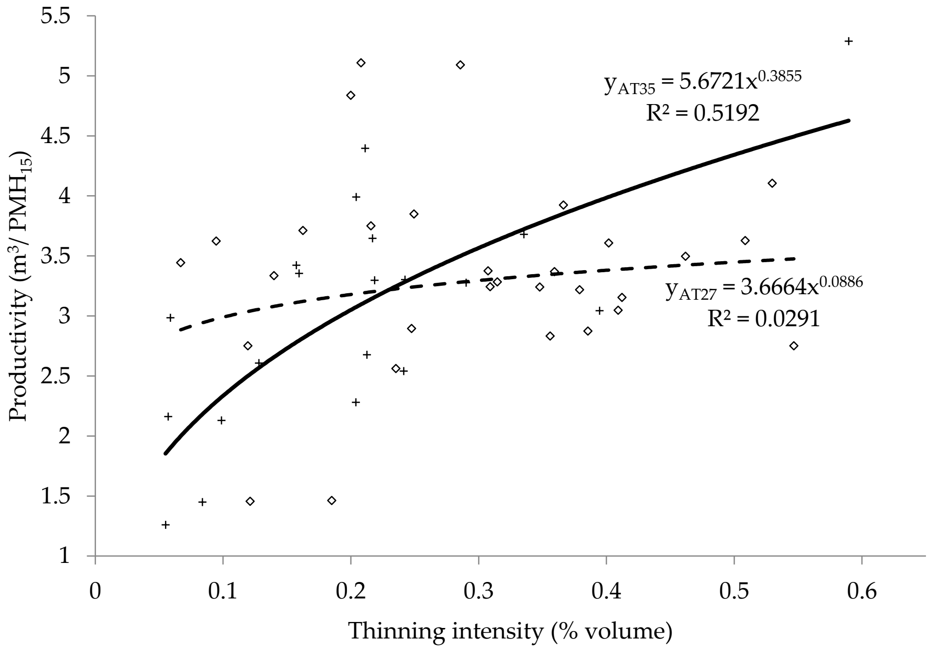

Figure 3. Marginal productivity functions for Model 3 and Model 4 (Table 8; Equation (3)).

Analyses showed that during a one-shift work system (8 h/day, 210 days/year) machine usage was rather low and did not exceed 65%. The estimated net machine cost (excluding profit margin, Table 9) for the forwarding equipment was EUR 36.12/PMH, and that for the mini-harvester EUR 52.47/PMH. Under these conditions, the total harvesting cost was EUR 25.11/m^3. At an average tree volume of 0.08 m^3, the corresponding estimated mini-harvester cost ranged from EUR 17.7 to 20.9/m^3 (Figure 2). Furthermore, for a distance of 300 m, the expected productivity of the forwarding equipment was 4.29 m^3/PMH_{15} with an estimated net cost of EUR 8.4/m^3. The lines in Figure 4 were indicate the average productivity and cost for the forwarding equipment as a function of distance by average, constant speed, and fuel consumption (Table 1).

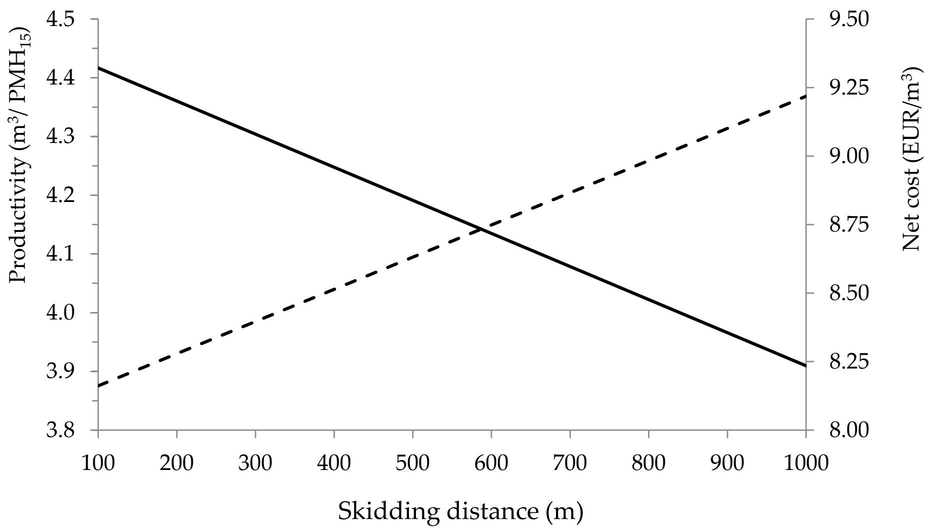

Figure 4. Productivity and costs as a function of forwarding distance (MTZ 952.2 universal tractor with FAO FAR 842 trailer).

Table 9. Cost calculations in euros.

Total Costs	Annual	Monthly	PMH	m^3	Share in Total Cost (%)
Kubota KX057-4 excavator with Arbro 400 S harvester head					
Fixed	20,227	1686	19.42	6.01	30.7
Variable	14,472	1206	13.89	4.30	21.0
Operator	19,953	1663	19.16	5.93	30.3
Net (excluding profit margin)	54,651	4554	52.47	16.24	83.0
Gross (including 10% profit margin)	65,842	5487	63.21	19.56	100.0
MTZ Belarus 952.2 farm tractor with FAO FAR 842 logging trailer					
Fixed	7660	638	7.24	1.78	16.9
Variable	13,057	1088	12.34	3.03	28.7
Operator	17,513	1459	16.55	4.07	38.6
Net (excluding profit margin)	38,230	3186	36.12	8.87	84.1
Gross (including 10% profit margin)	45,471	3789	42.96	10.56	100.0

Using the cost calculator developed by Ackerman et al. [36], it was estimated that an increase in machine usage rate to 80% would lower harvesting and forwarding costs to EUR 22.07/m^3 (Table 10). At an average stumpage price of EUR 35.46/m^3 for timber sold for industrial purposes [42], the net profit would range from EUR 9.8 to 13.4/m^3 depending on the usage rate (excluding VAT and the internal administration costs of the State Forests National Forest Holding).

Table 10. Expected net costs as a function of utilization rate.

Utilization Rate	Kubota KX057-4 Excavator with Arbro 400 S Harvester Head		MTZ Belarus 952.2 Farm Tractor with FAO FAR 842 Logging Trailer	
	EUR/PMH	EUR/m^3	EUR/PMH	EUR/m^3
0.6	53.41	16.53	37.15	9.13
0.7	49.24	15.24	34.05	8.37
0.8	46.12	14.27	31.73	7.80

4. Discussion

Based on delimbing speed the Arbro 400 S stroke harvester head (0.4 m/s) and a farm tractor coupled to a logging trailer were obviously less effective than a roller-feed harvester [43] (e.g., KETO Forst Silver 4.0 m/s). Despite this, the productivity of the excavator–harvester head combination was similar to that of some purpose-built feller-bunchers, such as the Moipu 400 E, which achieved 3.16 m^3/PMH_{15} [44]. Importantly, the low overall harvesting costs (EUR 22–25/m^3), which were approximately half of those reported for the aforementioned feller-buncher, are attributable to small fuel consumption (2.2 dm/PMH, Table 1), lower machine purchase and regional labor costs, and economical technology, which did not involve chipping, which is a very energy-intensive step in biomass production [45,46]. The forwarding costs calculated in the present work (EUR 7.8–9.13/m^3) are lower by EUR 3–6/m^3 than those determined by Spinelli and Magagnotti [47] for a new mini-forwarder model specifically designed for thinning operations.

It seemed obvious that mini-harvester productivity would increase with thinning intensity because a stationary machine can fell several trees within the reach of the crane at a high intensity, especially if the cab can turn 360° as is the case with the Kubota excavator. The absence of this correlation on sample plots along the narrow access trails is probably attributable to the longer time needed to maneuver the mini-harvester into position since the width of 2.7 m is the absolute minimum for harvesting [9].

However, at a thinning intensity of up to 23%, harvesting productivity was higher on sample plots established along the narrow access trails (AT27) as opposed to those along the wide access trails (AT35). This fact could be explained by the change to multi-tree handing and the forming of new passages with a width of 1 m and a length corresponding to the crane's outreach, which is known as boom-corridor thinning in the literature [43,48]. Multi-tree handling and schematic thinning may increase harvesting productivity by up to 30% and are typically used for felling narrow trees with a DBH of less than 8–10 cm [49,50]. They are less often employed on plots along wide access trails (AT35). In addition, Mederski et al. [51] did not find a simple correlation between thinning intensity and productivity. Given the results, this appears to be a characteristic feature of young tree stands. Interestingly, according to Ackerman et al. [52], an appropriate planting geometry may enhance productivity by approx. 8% and reduce harvesting costs by up to 7%.

The productivity of the mini-harvester and the tractor–trailer equipment varied by 22–52% and 16%, respectively, between plots (Table 5), which is not much compared to the productivity discrepancies (0.64–8.3 m^3/PSH) reported by Erber et al. [49] in small-diameter hardwood thinning by means of multiple-tree processing.

However, it should be stressed that this paper assessed the productivity of harvesting industrial roundwood having a minimum diameter of 5 cm inside bark. According to a study on the aboveground biomass allocation of Scots pines [53,54], the percentage share of merchantable wood ranges from 73 to 77%, depending on the biosocial position of the trees. As can be calculated from the tree volume tables for this stand of 25-year-old Scots pines [55], the results should, for energy purposes, be multiplied by a factor of 1.36 to ensure mini-harvester productivity in an industrial roundwood system for harvesting fractions of wood with small dimensions.

5. Conclusions

The aim of this study was to estimate the productivity of harvesting industrial roundwood during the first commercial thinning. The productivity of the track mini-harvester was found to range from 3.09 to 3.47 m^3/PMH_{15}, and that of the forwarding equipment was 4.07 m^3/PMH_{15} and the calculated net machine costs for analyzed machines were EUR 52.47/PMH and EUR 36.12/PMH, respectively. Moreover the estimated models of productivity as a function of tree volume indicated statistically significant findings, but the thinning intensity was significant only on plots along wide access trails (3.7 m). The productivity of schematic tree extraction with the trail clearing showed a smaller rise with the increase in tree volume. The absence of correlation on sample plots along the narrow access trails is probably attributable to the longer time needed to maneuver the mini-harvester into position since the width of 2.7 m is the absolute minimum for harvesting.

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