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The Effect of Technological Progress on Yarder Productivity: An Example from the Bulgarian Mountains

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Abstract: In recent years, a significant import of modern tower yarders has been registered in Bulgaria, where official productivity standards are routinely used for operational planning and control. Given the higher potential of the newer yarder models, the Bulgarian forestry sector has started a review of the older productivity standards dating back to the 1970s. This new endeavor has offered an ideal opportunity for gauging the effect of technological progress in yarder technology. Therefore, the authors have used the very first results achieved during the development of the new standards for conducting a preliminary quantitative comparison between older and newer yarder types. Modern yarders (e.g., Konrad Mounty 4000) are much faster than the older ones (e.g., Koller K300), and their time consumption per cubic meter is half as large, especially on longer distances. At short distances, however, their performance evens out. Regardless of the distance, the installation time of the Konrad Mounty 4000 is twice as short. As they are largely automated, the new machines can be manned by smaller crews (e.g., two workers instead of three) and are easier and safer to operate. Finally, the new machines are equipped with built-in loaders and processors, which allows them to integrate delimbing, crosscutting and stacking within the same work cycle. With older models, a separate team must be deployed for those tasks.

Keywords: productivity; efficiency; logging; mountain; modeling

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1. Introduction

Over 50% of the growing stock of Bulgarian forests is located on steep terrain, such that utilization requires cable extraction. For that reason, in the 1950s and 1960s, a large number (120) of long-distance Swiss-made Wyssen cableways (Wyssen sledge yarders, Wyssen Seilbahnen AG, Reichenbach, Switzerland) were put into operation, a dozen of which still operate in the Central Stara Planina region (Central Balkan). That number was further supplemented by about 300 Bulgarian-made Pioner cableways. In the 1970s, however, the use of long-distance cableways sharply decreased and was replaced with forestry-fitted farm tractors, which were cheaper to purchase and easier to operate.

The preference for tractors delayed the introduction of modern tower yarders, which found an additional obstacle in the prolonged financial crisis following the economic transition (1989–2010), which deprived forestry of investments for 20 years. The lack of a suitable yarding fleet made a considerable part of the wood stocks unavailable or made their exploitation difficult and expensive. For a long time, Bulgarian loggers have used a small number of compact tower yarders, very similar in design and performance to the better-known Koller 300 (Koller Forsttechnik GmbH, Schwoich, Austria), which has been a global best-seller for many decades and is still used today, often in combination with tractors and forwarders [1]. When those machines were used, harvest planning was based on dedicated yarding productivity standards, developed during the 1970s in the Czech Republic and adopted in Bulgaria due to their high quality and general reliability [2].

The dramatic reduction of the Bulgarian forest workforce observed since 2015 made mechanization a strategic necessity, and by 2022 the renewed Bulgarian forest fleet included 50 harvesters, 150 forwarders, 80 tower yarders and 15 mountain harvesters. The introduction of modern tower yarders required a general revision of the older productivity standards developed for cable yarding in the 1970s.

The purpose of the present work is to estimate a new productivity model for a modern medium-sized tower yarder deployed under Bulgarian conditions and to compare the model's predictions with those of the older productivity standard [2]. That is the preliminary step to developing a proper productivity standard for the new machines which can be used in operational planning.

2. Materials and Methods

Description of the experiment: our study focused on the cable extraction of softwood timber with the Konrad Mounty 4000 (KONRAD Forsttechnik GmbH, Preitenegg, Austria) mountain harvester, a combination of a tower yarder and a cut-to-length processor mounted on a truck. The machine was observed in the summers of 2020 and 2021 during commercial operations conducted on the Rhodopes mountains. At the time, the machine was engaged with salvage logging and thinning operations. The crew consisted of two men: a yarder and processor operator and a choker setter. Trees were felled by chainsaw by a third man, working ahead of the yarder crew, who took care of extracting whole trees to the roadside and delimbing, measuring and crosscutting them with the processor. The crew members were 40 years old, with 20 years of experience in logging. At the time of the study, they had already accumulated three years of experience with a Mounty 4000.

The official working time in Bulgaria is 8 h. The time for one shift in mountain conditions is 10 h, which includes the time to go to the site and return. The traditional productive time is 6 h, in good weather.

Test site: the observational study was conducted on several cable corridors in the Smolyan State Forest, in two natural mixed stands of spruce (*Picea abies* Karst.) and Scots pine (*Pinus sylvestris* L.) growing at an altitude of 1400 m asl. Compartment 194-m was a 110 years-old spruce-dominated stand that was being salvaged after heavy windthrow: mean tree height was 25 m and diameter and breast height (DBH) was 34 cm. Compartment 3123-p was a 70-years-old pine dominated stand that was being thinned from below: mean tree height was 21 m and mean DBH was 28 cm. The terrain was steep at both sites, with a slope gradient between 55 and 65%. In accordance with the age and type of felling, large wood (65%) predominated in the yarded mass.

Equipment: The cable yarder Konrad Mounty 4000 is factory equipped with a crane processor. Such a combination is known as a "mountain harvester" because it works—based on wood-removal roads—on slopes inaccessible to ordinary harvesters and forwarders. In the present work, the mountain harvester was equipped with a Woody H 50 processor (KONRAD Forsttechnik GmbH, Preitenegg, Austria) for delimbing, measuring and crosscutting stems up to 50 cm in diameter. Unlike newer models from the same manufacturer, the Mounty 4000 can only move its load uphill. This is suitable for the Rhodopes, where truck roads run along the ridges.

The carrying capacity of the Mounty 4000 (3 t) is higher than that of the older and lighter machines (1.5 t), taken as the control. Assuming that the optimal payload is approximately half of the carrying capacity [3,4], the optimal payload of the Mounty 4000 is about 1.5 t. At a density of freshly harvested softwood of about 1 t/m^3, the optimal load has a volume of approximately 1.5 m^3.

The Mounty 4000 was equipped with a carrier MM-SHERPA MOT II (MM Forsttechnik, Frohnleiten, Austria) with a load capacity of 4.0 to. The skyline diameter was 20 mm and the skyline length 550 m.

The typical application of the Mounty 4000 with the Woody H 50 processor is second and third thinnings in pre-mature stands. Trees with a breast-height diameter of 25–45 cm are felled, extracted to the roadside and processed with the integral processor. In mature stands, however, whole trees exceed the capacity of both the yarder and the processor, and therefore they are generally handled as tree sections. To that end, the crown is severed from the limb-free trunk and the two are extracted and processed separately.

Measurements. Data were collected through a cycle-level time study. One cycle consisted of a full turn and the respective record included the following data:

T_m—cycle time, min, including 15 min breaks,
L—yarding distance, m;
V—payload, m^3;
B—lateral haul distance, m;
N—piece count per cycle (trees or tree parts).

Cycle time was measured with a stopwatch and included all the time necessary to move the empty carriage to the loading site, load the carriage, move the loaded carriage to the unloading site (road) and unload the carriage. Since processing would proceed concurrently with the above-mentioned tasks, the time required for that task was not recorded separately but was considered as being embedded into the cycle time as a whole. Delays lasting less than 15 min were included in the cycle duration without being recorded and analyzed separately. Therefore, cycle time represented productive time including delays <15 min, noted as PSH15. For simplicity, cycle time was reported as minutes.

The yarding distance was measured separately for each cycle and represented the distance along the sky line that separated the loading site to the unloading site (i.e., the yarder pad).

The lateral haul distance was measured for each cycle as the distance between the stump site and the skyline, taken perpendicular to the skyline, regardless of the actual path followed by the load for reaching the carriage, which was generally longer due to the fact that most lateral hauling is performed at an angle from the skyline, not perpendicularly. This is a convention that simplifies measurements and has been adopted in many other studies of the same type—and especially those that had led to the development of the older standards. The lateral haul distance was recorded as 0 if the stump of the felled tree happened to be immediately adjacent to the cable corridor.

This study did not include an analysis of non-workplace time (travel, etc.), non-work time (delays) or supportive work time (including the set-up time and take-down time of the cable line).

Overall, the database included 264 yarding cycles, 220 of which were recorded in the windthrow area (compartment 194-m) and 44 in the thinning (compartment 3123-p).

Data processing. Statistical data processing was performed using the IBM SPSS Statistics software version 21. First, we estimated the main descriptive statistics for the results obtained from the two different compartments; then, we performed unpaired comparisons between the two compartments, using non-parametric techniques that would be robust against the effect of dataset imbalance and to eventual violations of the main parametric assumptions; finally, we estimated regression equations for time consumption (dependent variable) as a function of relevant independent variables (e.g., payload, distance, lateral distance, etc.).

3. Results

Table 1 reports the average values for cycle time, load size and all the other parameters measured during the study. The table also reports their minimum and maximum values, as well as the 5th and 95th percentiles of their empiric distribution.

Table 1. Descriptive statistics.

Parameter	Unit	Mean	Min	Max	$P_{0.05}$	$P_{0.95}$
T	min	7.9	1.5	16.0	4.0	11.7
V	m^3	0.939	0.120	2.120	0.394	1.476
N	count	1.57	1	3	1	2
L	m	154.1	8.0	370.0	40.0	348.0
B	m	12.6	1.0	27.0	3.0	23.0
v	m^3	0.65787	0.102	1.800	0.300	1.210
t	min/m^3	9.6	3.2	37.9	4.9	18.2

T—cycle time, including 15 min breaks; V—payload; N—piece count per cycle; L—yarding distance; B—lateral haul distance; v—piece size; t—time consumption per unit.

Table 2 compares the results obtained for the two forest compartments (i.e., compartment 194-m and 3123-p). They have equal payload and time consumption t. The stand 3123-p has a larger yarding distance. The lateral haul distance is exactly the same, perhaps because it is controlled by a regulation [5].

Table 2. Forest stands parameters.

Forest Stands	T	L	B	V	N	v	t	Slope	BHD	Altitude
	min	m	m	m^3	Count	m^3	min/m^3	Degree	cm	m
194-m	7.9	147	12.6	0.94	1.51	0.683	9.6	32°	34	1400
3123-p	8.3	195	12.6	0.92	1.90	0.520	9.8	28°	26	1500
p-Value [1]	0.064	<0.001	0.952	0.842	<0.001	<0.001	-	-	-	-

[1] estimated with the Mann–Whitney non-parametric test.

The following cycle time equation was fitted:

$$T = a_1 V + a_2 N + a_3 LV + a_4 BV, \tag{1}$$

wherein a_1, a_2, a_3, a_4 are regression constants, while the variable notations are those reported above. Dividing (1) by the payload yields the equation below:

$$t = a_1 + \frac{a_2}{v} + a_3 L + a_4 B. \tag{2}$$

The regression coefficients are given in Table 3a. More details about the regression results are given in Table 3b.

Table 3. (**a**) Regression coefficients; (**b**) Model summery.

(**a**)

Coefficient	Value
a_1	1.588
a_2	1.119
a_3	0.149
a_4	0.017

(**b**)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.983	0.966	0.965	1.53630

The goodness of fit for our model can be visually assessed from Figure 1. An even better fit might be obtained by integrating such independent variables as slope and silvicultural treatment in the equation. However, this study did not include a large enough variation for those variables, and unexplained variability is probably caused more by the erratic occurrence of short delays than by any other causes.

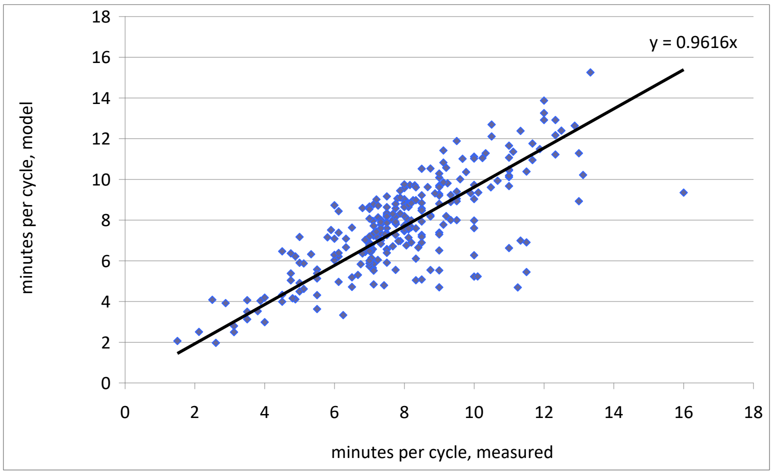

Figure 1. Scatterplot–comparison of the measured cycle time with the calculated one.

The predictions obtained from Equation (2) are printed in Table 4 to offer a numerical view of time consumption. The same predictions are shown as a graph in Figure 2. The thick line, calculated at a yarding distance of 0 m, shows the net loading and unloading time, while the dashed lines in the upper part of the graph represent an extrapolation of the data for longer distances than actually explored by the study; as such, they should be used with much caution.

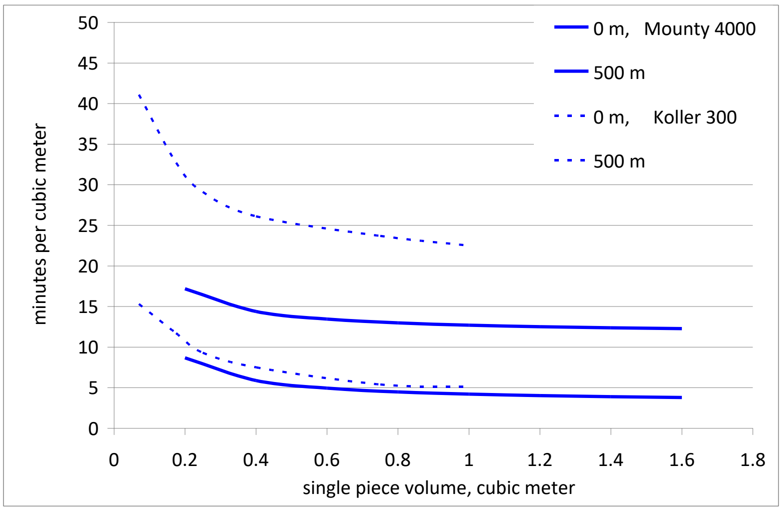

Figure 2. Comparison of cable yarders from the 1970s ([2], Koller 300) with modern ones (Mounty 4000) at extreme distances. Time consumption in a function of piece size. Uphill extraction, lateral haul distance 10 m.

The average payload (0.94 m^3) is much smaller than the optimum one (1.5 m^3). This suggests that an additional tree feller may be needed in order to fully utilize the potential of the new machine. On the other hand, the range of payload size (0.394 to 1.476 m^3) approaches, with its upper limit, the maximum carrying capacity of the older and lighter yarder models, which has been taken as the reference for the once-dominant older technology (1.5 m^3). This indicates that machines in that class may have difficulty removing whole trees from similar work sites. In contrast, the range of yarding distances (40 to 348 m) is within the same capabilities as that of the old machines.

Table 4. Time consumption per unit, for different yarding distance and piece size, lateral haul 10 m.

Single Piece Volume	**Yarding Distance**					
	0 m	**100 m**	**200 m**	**300 m**	**400 m**	**500 m**
m^3	**Minutes per Cubic Meter**					
0.2	8.67	10.37	12.07	13.77	15.47	17.17
0.4	5.88	7.58	9.28	10.98	12.68	14.38
0.6	4.94	6.64	8.34	10.04	11.74	13.44
0.8	4.48	6.18	7.88	9.58	11.28	12.98
1.0	4.20	5.90	7.60	9.30	11.00	12.70
1.2	4.01	5.71	7.41	9.11	10.81	12.51
1.4	3.88	5.58	7.28	8.98	10.68	12.38
1.6	3.78	5.48	7.18	8.88	10.58	12.28
1.8	3.70	5.40	7.10	8.80	10.50	12.20
2.0	3.64	5.34	7.04	8.74	10.44	12.14

Figure 2 compares the performance of the Mounty 4000 estimated through our equation with the performance of the older machines (Koller 300 class yarders) estimated through the reference Czech standards of 1972 [2]. At very short (0 m) longitudinal (!) yarding distances, the time consumption of the two systems is practically the same, indicating that both take approximately the same time to load and unload. However, the difference increases dramatically with the yarding distance, given the higher travel speed offered by the new machine. Overall, the performance of the new yarder is 1.3 to 2 times larger than that of the older machines. Furthermore, the new machine has a higher carrying capacity which allows whole-tree extraction in relatively old stands; this leads to faster mechanical processing and easy biomass recovery, both of which might be difficult to achieve at a lower carrying capacity.

While this study only focused on productive work time, set-up and dismantle times are also relevant components of cable operations and are expected to be faster for new, optimized machines [6]. Therefore, we compared the predictions obtained from [2] with those produced from a more recent work published in Austria for modern machines in the same class as the Mounty 4000 [7]. The results of that comparison are reported in Figure 3, which shows how the new yarders are almost twice as fast to set up and dismantle compared to older models.

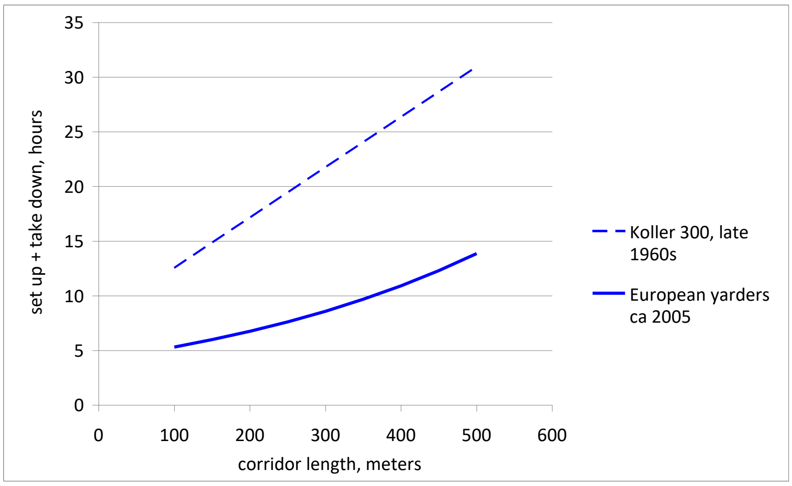

Figure 3. Installation time comparison (simple corridors, uphill extraction, 1st corridor). Koller 300 after [2], modern yarders after Stampfer et al. [7].

4. Discussion

Explaining the model. After testing several models, we opted for the simple and logical Equation (1), which is a linear function. The equation is able to account for the most important effects and it is easy to explain: the expression $aV + bN$ calculates the duration of the loading and unloading task and it conforms to the well-established piece-volume principle (Stückmassengesetz) [8,9], which states how time consumption per unit of volume is inversely proportional to piece size. Essentially, you only hook one piece at a time, and the hooking time per cubic meter will then decrease with piece size. The expression $cBV + dLV$ estimates carriage travel between the loading and unloading site and back, and represents the relationship between travel time, distance travelled and load size. Obviously, travel time will increase with increasing distance and load size. In that regard, a marked reduction of carriage speed was observed for payloads larger than 1 m^3. Equation (2) is equivalent to (1).

Comparison with other similar models. As a first step, we endeavored a conceptual comparison between our model and some similar yarding models available in the literature. This would help us check the formal validity of our own equations and at a same time evaluate the different approaches one could adopt when developing yarder productivity standards, with a view to further steps to be taken for developing our equations into such standards.

Şentürk et al. [10] presented three equations for predicting the cycle time of a Koller 300 yarder used in Türkiye. The three equations offer separate predictions, respectively, for the yarding distances of 100, 200 and 250 m. The equation for the yarding distance of 200 m is:

$$T = 3.592 + 1.440V + 0.300N + 0.001L + 0.129B. \tag{3}$$

T—cycle time, PSH_{15};
V—payload, m^3;
N—piece count per cycle (trees or tree parts).
L—yarding distance, m;
B—lateral haul distance, m;

The authors report significant deviations between the estimated and the observed cycle time, which may depend on the exclusion of terrain characteristics from the predictors. Equation (3) is linear, just like our Equation (1), but it differs from it for the presence of a constant term and for the fact that it does not include the possible effect of load size on travel time. This may limit the application of Equation (1) to small-tree operations only, where the payload may remain consistently below the actual loading capacity of the machine. Given that the Koller 300 is one of the smallest professional yarders on the market, that limit can be easily exceeded in all other applications, and the larger payloads thus accumulated are most likely to pose a challenge to the relatively small power unit supporting the machine, which could result in a significantly slower travel speed.

A similar approach was taken earlier on by Huyler and LeDoux [11], modeling the performance of the same machine model (Koller 300), used this time in the northeastern USA. Cycle time was again modelled as a function of payload, piece size, yarding distance and lateral yarding distance, as shown in Equation (4).

$$T = a_0 + a_1 V + \frac{a_2}{v} + a_3 L + a_4 B \tag{4}$$

T—cycle time, PSH_{15};
V—payload, m^3;
v—piece size, m^3;
L—yarding distance, m;
B—lateral haul distance, m;

This equation is also linear, and it was validated for payloads close to optimum, while it would return a large error for single undersized trees. The piece count N is also included—if implicitly—given that $1/v = N/V$.

A completely different approach was followed in Austria, Erber et al. [12], who used a unit-level time study—not a cycle-level one—to develop the following equation, capable of estimating the time consumption of a Koller K507 yarder (Koller Forsttechnik, Schwoich, Austria):

$$t = a_1 + \frac{a_2}{v} + a_3\lambda + b_1\delta + b_2\eta, \tag{5}$$

t—time consumption per unit, PSH_{15}/m^3;
v—piece size, m^3;
λ—span length, m;
δ—yarding direction (uphill or downhill);
η—silvicultural treatment (thinning, regeneration cut, salvage logging, ...);
a_1, a_2, a_3, b_1, b_2—regression constants.

This equation is linear and derives from a unit-level time study where each observation is a whole corridor, not a cycle like in our study. For that reason, the equation does not integrate lateral yarding distance and uses span length (the length of the cable corridor) instead of actual yarding distance, whose average value can be approximated to half the span length, $\overline{L} \approx \lambda/2$, except in those rare cases when the yarder cannot be installed right next to the cutting area. Being based on a unit-level study, Equation (3) is somewhat less accurate when used to predict a single operation or a subset of it, but it is likely sturdier and it integrates such variables as slope gradient, extraction direction and silvicultural treatment, which are missing from our equation. The derivative $\partial t/\partial L$ of the curves set by Equations (1) and (3) is a constant. This reflects the fact that movement time does not depend on loading complexity (represented by N), unlike loading time. In Bulgaria, Stoilov investigated the Koller K501 truck-mounted tower yarder in the particular case of a single deciduous mature forest stand and accordingly obtained a simple equation [13].

While most authors have modeled cycle time with linear equations, there are few interesting exceptions. Among them, Opeka [3], who modeled cycle time for uphill and downhill extraction with a Mayr-Melnhof Syncrofalke yarder (MM Forsttechnik GmbH, Frohnleiten, Austria) in Slovenia, on both coniferous and deciduous forests. The model developed by Opeka is:

$$T_m = N^{n_1} L^{n_2} B^{n_3} H^{n_4} \tag{6}$$

T_m—cycle time, min, including 15 min breaks;
N—piece count per cycle (trees or tree parts).
L—yarding distance, m;
B—lateral haul distance, m;
H—carriage height, m.
n_1, n_2, n_3, n_4—regression constants.

Payload is not included among the predictors (independent variables), perhaps because it is approximately constant if the crew is keen to optimize productivity. The equation includes carriage height as one of the predictors, which is indeed sensible, and yet of little practical use, because that information is difficult to know in advance unless the harvest plan is so detailed as to include a desk calculation of all individual lines. Equation (6) uses a power function to estimate cycle time, and it can be linearized by logarithmization. In this equation, ∂t⁄∂L is not a constant.

Equations (3) and (6) contain the piece count N in an explicit form, and Erber's Equation (5) contains it in an implicit form. According to an extensive study by Böhm and Kanzian [14], only 22% of yarder extraction models known to them include this parameter. However, without it, the piece volume principle, which governs the composition time of the payload, cannot be applied.

Finally, a very interesting approach is the combined model developed in Austria by Ghaffariyan et al. [15] for the same Mayr-Melnhof Syncrofalke yarder studied by Opeka, as well as for the smaller Mayr-Melnhof Wanderfalke. The equation is:

$$T_m = 0.601v^{-0.3} + 0.005L + 0.092B + 0.018P + 0.038\alpha + 1.125\tau, \tag{7}$$

T_m—cycle time, min, including 15 min breaks;
v—piece size, m^3;
L—yarding distance, m;
B—lateral haul distance, m;
P—removal percentage (%);
α—the slope of the terrain (%);
τ—cable yarder type (0 for Syncrofalke, 1 for Wanderfalke);

The equation is the combination of a linear and a power equation, and has a high explanatory power (R^2 = 0.90). Contrary to a pure power Equation (6), it cannot be linearized.

In this equation, both the piece count and the payload are accounted for, although implicitly, due to the following relationship:

$$v^{-0.3} = \frac{N^{0.3}}{V^{0.3}}.$$

Use of the model. Equation (2) is valid for extraction with modern high-performance cable yarders such as the Mounty 4000. On the contrary, the older productivity standards used so far in Bulgaria [2] do not provide a good representation of new technology: however, they can still be used for lighter and simpler machines, like the Koller K300 and its recently updated version, the K300 K. In fact, a main difference between the Mounty 4000 and the older yarders is that the former is fitted with an integral processor. Therefore, while both the new and old productivity models are good for predicting extraction productivity, the productivity model developed here for the new machine integrates processing the trees into logs, a task that is not included in the older model [2]. If the two models can be used to compare extraction productivity, they cannot be used as such for the same operational purpose, because deployment of an older cable yarder will require the scheduling of two teams: one for extraction with the yarder, and the other for processing the extracted trees into logs. In contrast, the productivity model for the Mounty 4000 is enough to predict both tasks, since a separate processing machine and team is not needed. Furthermore, the two models apply to different crew sizes. The Mounty 4000 and the other machines in the same class are highly automated and can extract with a crew of two; conversely, the older machines covered by the MLVH model are much simpler and they require a crew of three. This must be considered when interpreting the results of the two different models.

Input data. Equation (2) can be fed with input data easily extracted from the management plan: this is a big practical advantage when using the model for harvest planning purposes. Average stem volume can be estimated with sufficient accuracy from the inventory data or from a growth table. Payload can be deduced from the technical specifications of the machine, or from the experimental data obtained from this study. Then, the number of trees per turn is easily obtained by dividing payload by stem volume. If the number is smaller than one, the calculation indicates that whole trees will have to be crosscut into whole-tree sections in order to facilitate extraction. Finally, yarding distance and lateral yarding distance can be easily assessed by consulting the compartment maps. There, one can simply identify suitable landings and sketch from there a network of cable corridor capable of covering the harvest area. From that basis, one can easily estimate mean extraction and lateral extraction distance.

Productivity standards for cable yarding. Productivity standards are a practical tool for operational planning and control. The equation produced from this study can be used as the basis for developing such a standard. Based on selected compartment data, our equation estimates productive cycle time, including delays up to a maximum event duration of 15 min. In order to predict actual scheduled time, one has to account for auxiliary work and delays longer than 15 min.

The most important component of auxiliary work in cable operations is set up and dismantle. The time devoted to those operations can be estimated using the equations reported by Stampfer et al. [7], who offer solid and updated models. Ideally, those models should be calibrated for the different work conditions that might be found in Bulgaria, or anywhere else the model is going to be used. In particular, the models developed by Stampfer et al. [7] focus on simple corridors, where one can use existing trees for the tail mast and the eventual intermediate supports. The model also indicates that the ratio of set-up time to dismantle time is 18:8. Corridor survey and marking (including selection of anchors, intermediate spars, etc.) is estimated to take 0.2 min per linear meter, especially if visibility is low, vegetation is dense and slope is very steep.

Concerning major delays, they are erratic by nature and therefore they are quite difficult to predict, if not in the long term. That said, delay events lasting up to 15 min represent over 90% of total delay time: therefore, one may simply inflate the productive time estimated through the current equations by 10% (i.e., multiply it by 1.1) in order to obtain the scheduled time, excluding set up and dismantle, which are calculated separately, as shown above.

Technological progress. If we take the Mounty 4000 as a representative sample of modern yarding technology, then the productivity increase derived from 50 years of technological progress in the specific field can be estimated between 30% and 100%. Based on the results in Figure 2, most of the productivity increase depends on a faster carriage speed, given that the loading and unloading time is marginally shorter with the new machine. In fact, pure productivity is just one of the benefits, and maybe not even the most important. The new yarder features higher automation and task integration: therefore, it can be operated by a smaller crew and tasked with processing, as well. In contrast, the older yarder requires an additional crew member (i.e., three instead of two) and cannot be tasked with processing, just with extraction. Processing must be performed by an additional crew working alongside which picks the trees from under the tower, processes them into logs and stacks the logs along the forest road. Previous studies indicate that the productivity and economic benefits of mechanized processing are quite large, possibly larger than the benefits accrued by deploying a newer and faster yarder alone. At the same time, ergonomics and work safety are much improved, which results in better jobs [16]. Most of the older technology represented by the MLVH standards is no longer compliant with European work safety regulations and has been adapted to match the current stricter standards: for instance, the older Koller K300 is no longer sold in Europe, where it has been replaced by its upgraded and compliant new version, the K301.

5. Conclusions

Over the past 50 years, tower yarder technology has made great advances in productivity, ergonomics and safety. This is especially the case for the large self-propelled tower yarder models that have appeared recently, which often integrate a loader and a processor. Such new machines offer faster cable speeds and are easier to set up and dismantle compared with the older and smaller trailer-mounted models. For that reason, productivity standards may need to be updated for efficient operational planning and control.

The particular findings on which our general conclusion is based are:

1. Over the last 50 years, there have been great advances in transportation speed, but manual loading operations have not changed much.
2. Set-up and dismantle time has halved.
3. If there should be a single national standard for cable yarder transportation, it should be based on large tower yarders. Small yarders will be able to meet such a standard in the case of relatively small material and short yarding distances.

4. A major additional advantage, which we do not explore in detail in this work, is the automation of non-transport operations such as delimbing, measuring, crosscutting and stacking.

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