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RESEARCH ARTICLE

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Cost evaluation of three ground-logging methods in a mixed broadleaved mountainous forest

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Abstract

Aim of study: To compare cost and productivity of three ground-based logging methods by skidder: 1, tree length method (TLM), 2, long length method (LLM) and 3, short length method (SLM).

Area of study: A mixed broadleaved mountainous forest stand in the Hyrcanian forests in northern Iran.

Material and methods: To develop time prediction models, all measurements of time were replaced by their decadic logarithms, and on the basis of the developed models, we simulated cost of 11 skidding turns depending on the diameter of the log (DL), skidding distance (SD), and the winching distance (WD) for TLM, LLM, and SLM.

Main results: Our results demonstrated that on average the net costs per extraction of one cubic meter wood (m^3) were 3.06, 5.69, and 6.81 €/m^3 in TLM, LLM, and SLM, respectively, and the most economical alternative depending on DL, SD and WD was a TLM. Furthermore, the results of simulated models suggest that as long as the diameter of the felled trees is less than 40 cm, the cut-to-length system is not an economical alternative. The cut-to-length method can be applied for trees with larger diameter (more than 40 cm), and in short skidding distance SLM is preferable to LLM but in cases of long skidding distance, LLM is more economical than SLM.

Research highlights: DLand SD were the main causes which influenced the productivity and cost of ground-based logging methods.

Additional keywords: tree length method; long length method; short length method; skidding unit cost; logarithm base 10.

Abbreviations used: DL (diameter of the log); DT (delay time of time consumption); LL (length of logs); LLM (long length method); NL (number of logs); SD (skidding distance); SL (slope gradient in the loaded direction); SLM (short length method); TLM (tree length method); WD (winching distance).

Authors´ contributions: : Conceived, designed and performed the experimental work: AB, JE, SAOH. Analyzed the data: AB, JE. Developed the concept and wrote the manuscript: AB, JE, RL. All authors read and approved the final manuscript.

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Introduction

Nowadays, due to technological evolution, evaluation of machine productivity and calculation of the average cost of skidding for each hour and each cubic meter is necessary to compare their efficiency (Demir, 2010). Measuring productivity and costs of forest equipment and forest harvesting alternatives is an important aspect of an forest industry in order to increase the efficiency and decrease the operating costs. To do so, the harvest planner must understand the cost characteristics of the available logging systems under the influence of parameters such as the tree size (volume), skidding distance, winching distance, skidding direction or ground slope and number of logs (McDonagh, 2002; Nurminen *et al.*, 2006; Jirousek *et al.*, 2007; Eghtesadi, 2008; Jourgholami *et al.*, 2008; Naghdi *et al.*, 2010; Barari *et al.*, 2011; Jourgholami & Majnounian, 2011; Ghaffariyan *et al.*, 2012; Gilanipoor *et al.*, 2012; Ghaffariyan, 2013). Moreover, quantifying these factors is not sufficient to evaluate the productivity and efficiency effects. Mechanized harvesting operations are popular in Australia because of their productivity and efficiency, improved worker safety and the reduced cost of operations (Alam *et al.,* 2012).

An important research tool which is common to compare the productivity of forest harvesting systems across varying conditions is time studies (Harstela, 1991; McDonald & Fulton, 2005; Nuutinen *et al.*, 2008; Ghaffaryan *et al.*, 2012; Mousavi & Nikooy, 2014). During the last decade, several studies evaluated the unit cost of ground-based cable skidders by used time study techniques. Their obtained unit net cost was as following: Parsakhoo *et al.* (2009), 1.32 €/m^3; Jourgholami *et al.* (2008), 4.20 €/m^3; Naghdi *et al.* (2010), 4.03 €/m^3; Gilanipoor *et al.* (2012), 3.70 €/m^3; Mousavi *et al.* (2012), 12.3 €/m^3 (13.9 \$/m^3); Lotfalian *et al.* (2011), 4.70 €/m^3; Barari *et al.* (2011), 7.29 €/m^3; Çalışkan (2012), 0.98 €/m^3 (1.1 \$/m^3); Hejazian *et al.* (2013), 4.12 €/m^3 and 3.3 €/m^3. Also, Naghdi & Bagheri (2007) and Ghaffariyan *et al.* (2012) found that in the ground-based cable skidder system, skidding phase in the cut-to-length method was more expensive than the tree length method, and Mousavi (2008) reported that LLM was more economical than SLM.

In a comparison of whole tree harvesting system cut-to-length involves the high initial cost of investment, repair and maintenance of the machine's complex computerized system, and the inability of the felling-processing machine to handle stems with stump diameter larger than 60 cm. However, whole tree harvesting requires more woods workers, supervision, and support than cut-to-length harvesting. In addition, the hourly machine rate for the whole tree method system has also been higher than for the cut-to-length (LeDoux & Huyler, 2001). Comparison productivity and costs of a skidder system (whole tree) and a forwarder system (cut-to-length) in southern Alabama showed that the productivity was limited by the woods transport vehicles, and weekly production rates were 261 cords for the skidder system and 249 cords for the forwarder system (Lanford & Stokes, 1996). A study in the eastern part of Canada showed that the wood production cost per cubic meter in assortment logging method was higher than full tree logging method (Favreau & Gingras, 1998). In the research area of Akay (1998) cost for cut-to-length system by using four sawyers and a forwarder was 9.96 €/m^3 and 12.4 €/m^3 in the Black Sea and Aegean regions, respectively, and cost for whole tree system by using four sawyers, a grapple skidder, and a loader was 8.2 €/m^3 in the Mediterranean region. Also, Adebayo (2006) found that the hourly machine rate for the whole tree method system was slightly higher than the cut-to-length harvesting system.

The main objective of this investigation is comparison cost and productivity of three logging alternatives (1- TLM, 2- LLMand 3-short SLM) depending on the DL, SD, and WD in ground-based cable skidders system in a mixed broadleaved mountainous forest.

Material and methods

Site description

This study was conducted in the compartments 46, 107 and 41 of Jo Jadeh district in the Wood Industry of Farim forests (a part of the Hyrcanian forests). Some characteristics of study compartments and harvesting alternatives in case study can be seen in Table 1. The elevation is approximately 445–2,250 m a.s.l (*i.e.*, above sea level) with a north and northwestern aspect. The original vegetation of this area is an uneven-aged mixed forest dominated by *Fagus orientalis* and *Carpinus betulus*, with the companion species *Alnus subcordata*, *Acer platanoides, Acer cappadocicum, Ulmus glabra* and *Tilia rubra*. The soil type is forest brown soil and the soil texture varies between clay-loam and silty-clay. The average annual rainfall recorded at the closest national weather station was 845.5 mm and the mean annual temperature is 11.5°C. The silvicultural system was applied as a combination of group- and single-tree selection. The total volume of primary transportation was carried out by skidders to landing areas that were prepared at the border of the road in the lower part of compartments. Timberjack 450C rubber-tired skidder used in this study was a normal articulated, four-wheel-drive vehicle weighing 10.3 ton (55% on the front and 45% on the rear axle) with an engine power of 177 hp (132 kW) and engine model of 6BTA5.9. It is equipped with a blade for light pushing of obstacles and stacking of logs. The skidder was fitted with tires the size of 24.5–32 inflated to 220 kPa on both front and rear axles, it had a ground clearance of approximately 0.6 m. Timber bunching was carried out by the winch that was installed in the near part of the skidder from the stump to the skidder and one end of the dragged round wood was in touch with the ground (Jourgholami & Majnounian, 2013). High, length and width of the machine was 3 m, 6.28 m and 3.1 m, respectively.

Table 1. Some characteristics of study compartments.

Alternative	Compartment No.	No. of skidding trips	Compartment area (ha)	Trees/ha	Total product (m^3)
TLM	46	30	66	205	307.04
LLM	107	31	39	153	292.87
SLM	41	41	85	260	311.59

TLM, tree length method; LLM, long length method; SLM, short length method).

Data collection

To estimate productivity and cost a continuous time-study technique was applied. Time for each work element and accumulated time were measured by a deci-minute stopwatch in minutes and seconds. A work cycle and time elements were same for TLM, LLM and SLM which broken down in seven phases (traveling unloaded, releasing, hooking, winching, traveling loaded, unhooking, pilling and delays). For each trip, important variables of the time consumption such as the size of logs (DL and length (LL) of logs), the number of logs (NL), terrain slope gradient in the loaded direction (SL), SD and WD were recorded.

Data analysis to estimate productivity rates and cost

Normally scientific who use time study in forest harvesting operations predict a time consumption model by using the original times which are gathered by time studies in the field. But in this paper, all time study numerical data were transformed to their logarithmic data based on 10 and the time consumption model was developed on the basis of logarithmic time data.

Why do we use logarithms?

Logarithm modeling is indeed the most reliable method for predicting the consumption of woodworking time. Today's concept of logarithms might make it seem strange that logarithms were really developed out of comparing velocities of arithmetically and geometrically moving points (Villarreal-Calderon, 2008). There are two reasons for this unusual and slightly more difficult method: *(i)* Specialists in mathematical statistics know that logarithms often fit better to time studies than numerical data (Sachs, 1984). *(ii)* Numerical data produces unsolvable contradictions and problems that do not occur with logarithmic data (Erler, 1984, 2012), *e.g.*, in time study numerical data, arithmetic mean and performance mean are different but in the logarithm of data, both performances mean and arithmetic mean are congruent. For example, to do a task by two employees, one employee needs 5 min and his/her colleague needs 15 min (their arithmetic mean is 10 min). The fast worker's performance is 12 times/h while his slower colleague's performance is only 4 times/h (their performance mean is 8 times/h). If this performance mean is recalculated to the arithmetic mean, it would be 7.5 min. This result highlights the two different arithmetic means to do a task, 10 min as the average time consumption and 7.5 min as the time for average performance, which can cause a lot of problems in the interpretation of the statistics (Erler, 2012). To solve this problem we present a solution, as the first, when all collected numerical data of the time study are transformed to their logarithm data based on 10. After calculating statistics parameter for the logarithmic data, they are recalculated into numerical figures again. The recalculated mean in our example is located between the two means (7.5 min < recalculated mean <10 min). Therefore, in this research we transformed all the time study data to their logarithms on the base 10, and using logarithmic data we developed three logarithmic time prediction models. Finally, by the used logarithmic models, we simulated the net cost for 11 skidding cycles depending on DL, SD, and WD in TLM, LLM and SLM. In order to compare the different logging methods under comparable conditions, the cost of 11 skidding turns was simulated by developed model under maximum, mean and minimum of the influence parameters such as NL, LL, DL, SD, WD, SL. Except LL value, maximum, mean and minimum of all influence parameter values were same for all alternatives which were calculated by used recorded data in TLM, LLM, and SLM. These parameters are depending on the terrain, and it is possible to harmonize them for all alternatives, but the length of log depends on the harvesting alternative and that makes the relevant difference between the harvesting alternatives (TLM, LLM, and SLM). Therefore, the value of LL has to be held different in the alternatives.

Prediction time consumption model and cost

The logarithmic time prediction models were developed on the basis of linear regression in SPSS software (SPSS, Tulsa, USA, Version 19, 2011). But only influencing factors with significant correlation coefficients at the level of significance $\alpha = 0.05$ were used to develop the logarithm models. Subsequently, by used logarithmic models, we simulated unit cost for 11 skidding cycles depending on DL, SD, and WD in TLM, LLM, and SLM. In order to estimate cost depending on DL, DL, NL, and LL were considered as influencing variables. The value of DL and NL were variable between 11 cycles and LL was variable between the alternatives (TLM, LLM, and SLM).However, other parameter values (such as SL, SD and WD) were same between 11 skidding turns which was set to the mean value. To estimate the cost depending on SD, SD and LL were considered as influencing parameters, and the value of SD was variable between cycles and LL was variable between alternatives, and the other parameters were set to the mean value. In order to estimate the cost depending on WD, WD and LL were considered as influencing parameters, which variable parameter between cycles was WD and LL was variable parameter between alternatives and the other parameters were set to the mean value in all 11 skidding turns in TLM, LLM, and SLM. Delay time of time consumption (DT) by prediction model in TLM, LLM, and SLM was measured as following (Eq. [1]):

$$DT = \frac{\text{Delay time of TLM+LLM+SLM}}{3} \qquad [1]$$

Results

Statistical arithmetic mean and logarithmical mean

The estimated time by the logarithmic models and the measured time on the field (real time) by time study techniques in TLM, LLM, and SLM are shown in Table 2. The ratio between the estimated time by logarithmic models and the measured time by the time study was 93% for TLM, 91% for LLM and 92% for SLM, as well as, values of geometric means are less than the time study numeric data (Table 2).

Logarithmic time prediction model for simulate 11 skidding cycles

TLM prediction model (Eq. [2]):

$$\begin{aligned}\hat{Y} = {} & 10^{(0.48 + 0.45 \times \mathrm{SD})}\, TU \\ & +10^{(-0.175 + 0.004 \times \mathrm{WD}) + (-0.24 + 0.1 \times \mathrm{NL})}\, R \\ & +10^{(-0.105 - 0.0005 \times \mathrm{DL}) + (-0.31 + 0.115 \times \mathrm{NL})}\, H \\ & +10^{(0.09 + 0.01 \times \mathrm{WD})}\, W \\ & +10^{(0.16 + 0.001 \times \mathrm{DL}) + (0.158 + 0.0035 \times \mathrm{LL}) + (0.158 + 0.064 \times \mathrm{SD}) + (0.24 - 0.015 \times \mathrm{NL})}\, TL \\ & +10^{-0.77}\, UH \\ & +10^{-0.23}\, P \end{aligned} \qquad [2]$$

Table 2. Statistical parameter values to compare arithmetic mean of numeric and logarithm data, and geometric mean.

Harvesting method	Work phase	Statistical parameter			Ratio %
		Arithmetic mean of numeric data	Arithmetic mean of the logarithm	Geometric mean of the recalculated logarithm	
TLM	Empty traveling	6.86	0.83	6.72	92
	Release	0.88	-0.15	0.70	82
	Hooking	0.79	-0.24	0.58	73
	Winching	2.77	0.32	2.07	75
	Travel loaded	6.99	0.83	6.74	99
	Unhooking	0.18	-0.77	0.17	93
	Pilling	0.69	-0.23	0.59	85
	Total	19.17		17.78	93
LLM	Empty traveling	11.31	1.00	10.11	93
	Release	1.93	0.17	1.49	85
	Hooking	1.83	0.02	1.05	57
	Winching	1.69	-0.73	0.19	84
	Travel loaded	8.95	0.92	8.35	99
	Unhooking	0.24	-0.75	0.18	69
	Pilling	0.75	-0.16	0.69	90
	Total	26.69		24.28	91
SLM	Empty traveling	4.93	0.68	4.78	97
	Release	1.10	-0.02	0.95	86
	Hooking	1.84	0.18	1.50	82
	Winching	2.26	0.09	1.23	83
	Travel loaded	6.67	0.80	6.31	95
	Unhooking	0.25	-0.76	0.18	70
	Pilling	1.11	-0.03	0.93	86
	Total	17.25		15.8	92

LLM prediction model (Eq. [3]):

$$\hat{Y} = 10^{(0.289 + 0.01 \times SL) + (0.217 + 0.365 \times SD)}\, TU + 10^{(0.004 + 0.0035 \times WD) + (-0.103 + 0.09 \times NL)}\, R + 10^{(-0.402 + 0.009 \times DL) + (-0.334 + 0.14 \times NL)}\, H + 10^{(-0.249 + 0.16 \times NL)}\, W + 10^{(0.196 + 0.007 \times SL) + (0.185 + 0.152 \times SD) + (0.227 + 0.031 \times NL)}\, TL + 10^{(-1.36 + 0.01 \times DL)}\, UH + 10^{-0.17}\, P \quad [3]$$

SLM prediction model (Eq. [4]):

$$\hat{Y} = 10^{(0.44 + 0.45 \times SD)}\, TU + 10^{(-0.098 + 0.005 \times WD) + (-0.26 + 0.1 \times NL)}\, R + 10^{(-0.21 + 0.15 \times NL)}\, H + 10^{(0.145 - 0.0023 \times DL) + (-0.036 + 0.003 \times WD) + (0.123 - 0.0053 \times SL) + (-0.104 + 0.047 \times NL)}\, W + 10^{(0.422 + 0.712 \times SD)}\, TL + 10^{-0.76}\, UH + 10^{-0.03}\, P \quad [4]$$

Ŷ is time consumption by model (min), LD is loading distance, TU is traveling unloaded, R is releasing, H is hooking, W is winching, TL is traveling loaded, UH is unhooking, P is pilling.

The most important affected factors in TLM were SD, WD, NL, and DL (Eq. [2]). In both cases of LLM and SLM the most important factors were SD, NL, WD, DL and SL (Eqs. [3] and [4]).

Unit net cost depending on DL, SD, and WD

The simulated cost models show that the mean net cost depending on DL (volume), SD and WD were 3.06, 5.69 and 6.81 €/m^3, respectively. In TLM the maximum net cost was 3.23 €/m^3, mean 3.06 €/m^3 and the minimum was 2.94 €/m^3; in LLM maximum cost reached 5.76 €/m^3, mean cost 5.69 €/m^3 and minimum of cost 5.63 €/m^3. And in SLM the queue was 6.97 €/m^3, 6.81 €/m^3 and 6.67 €/m^3 depending on the winching distance (Fig. 1 and Table 3).

Delay time in the prediction model

On average, 11, 12 and 15 % of the gross effective time of the time study was DT in TLM, LLM, and SLM, respectively. As mentioned in the methodological part, the DT to the prediction model was estimated by using the average of DT in time study in TLM, LLM, and SLM: DT = (11+12+15)/3 = 12.7%.

Discussion

According to our assumption all values of estimated time (geometric means) by logarithmic formulas were lower than the time study numerical data (lying between two means). Also, estimated time consumption by the developed models and real time

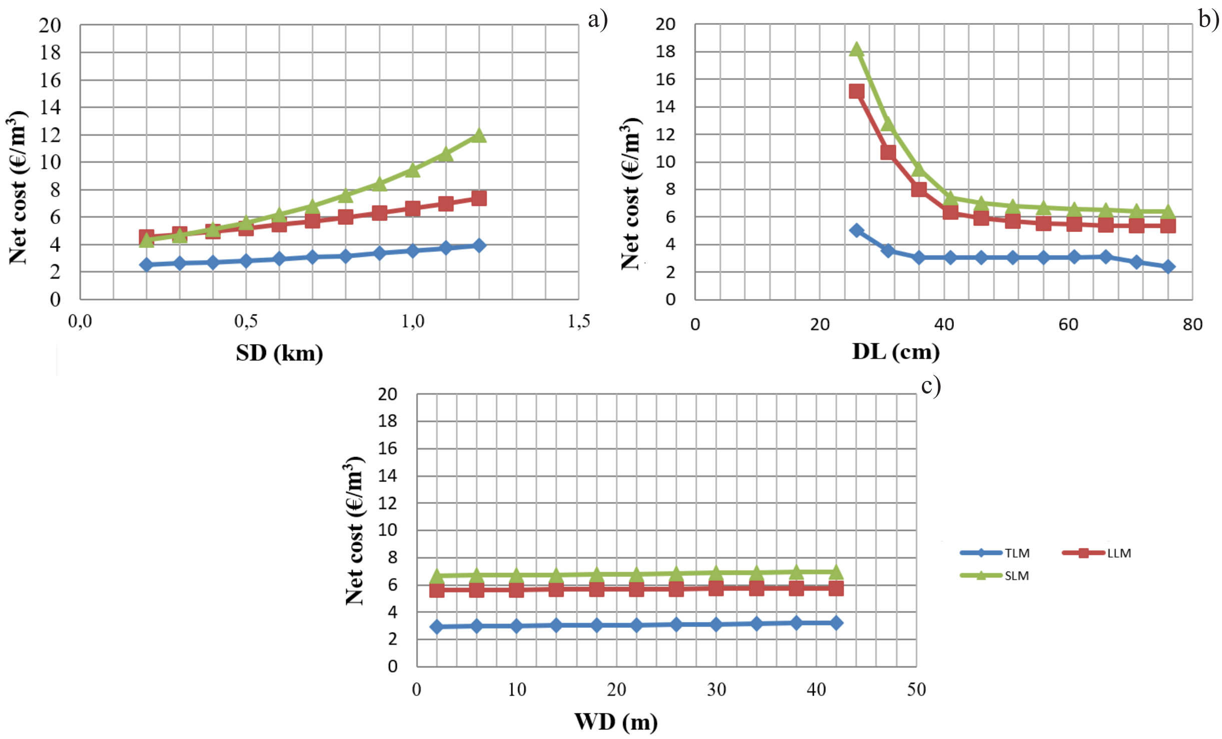

Figure 1. Net cost/m^3 depending on SD, skidding distance (a), DL, diameter of the log (b) and WD, winching distance (c) in TLM, LLM, and SLM.

Table 3. Gross and net effective costs depend on WD (winching distance), SD (skidding distance) and DL (diameter of the log), in TLM, LLM, and SLM.

Costs (€/m³)	TLM			LLM			SLM		
	Depend on			Depend on			Depend on		
	WD	SD	DL	WD	SD	DL	WD	SD	DL
Maximum gross effective cost	3.70	4.51	5.77	6.60	8.41	17.33	7.98	13.74	20.87
Maximum net effective cost	3.23	3.94	5.04	5.76	7.34	15.13	6.97	12	18.22
Mean of gross effective cost	3.51	3.51	3.51	6.52	6.52	6.52	7.80	7.80	7.80
Mean of net effective cost	3.06	3.06	3.06	5.69	5.69	5.69	6.81	6.81	6.81
Minimum gross effective cost	3.37	2.88	2.57	6.45	5.20	6.12	7.65	4.93	7.32
Minimum net effective cost	2.94	2.52	2.40	5.63	4.54	5.34	6.67	4.30	6.39

were at a close ratio, on average it was more than 91% (Table 2).

Knowing the factors affecting the production and costs of skidding has an important role in planning and organizing consumed budgeting, as well as, arranging expenditures to raise profitability (Hejazian *et al.*, 2013). Overall, after analysing the data and applying the skidding time prediction models, it became clear that the time consumption was affected mainly by the skidding distance, the winching distance, the number of logs, the diameter and length of log and the slope, which was in line with previous studies such as McDonagh, 2002; Jirousek *et al.*, 2007; Eghtesadi, 2008; Jourgholami *et al.*, 2008; Naghdi *et al.*, 2010; Barari *et al.*, 2011; Jourgholami & Majnounian, 2011; Ghaffariyan *et al.*, 2012; Gilanipoor *et al.*, 2012; Ghaffariyan, 2013. On the other hand, mechanized harvesting operations are popular in Australia because of their productivity and efficiency, improved worker safety and the reduced cost of operations (Alam *et al.,* 2012).

On average, the net cost for extraction of 1-m³ of wood was 3.06, 5.69 and 6.81 €/m³ in TLM, LLM, and SLM. These results are consistent with former studies about cost of ground-based skidders system (such as Jourgholami *et al.*, 2008; Parsakhoo *et al.*, 2009; Naghdi *et al.*, 2010; Lotfalian *et al.*, 2011; Çalışkan, 2012; Gilanipoor *et al.*, 2012; Mousavi *et al.*, 2012; Hejazian *et al.*, 2013). Furthermore, the results have presented that depending on DL, SD, and WD the most profitable alternative is TLM, also some researchers such as Favreau & Gingras (1998), Naghdi & Bagheri (2007) and Ghaffariyan *et al.* (2012) found that the skidding phase of the cut-to-length method was more expensive than tree length method, as well as Lanford & Stokes (1996) and Akay (1998) reported that production cost reduction with the alternatives that have the biggest dimension of wood. According to Adebayo (2006) hourly machine rate for the whole tree method system was slightly higher than the cut-to-length harvesting system. In the cut-to-length system, our result demonstrated that cost is dependent on DL, which in small diameter LLM is more economical than SLM but in the biggest diameters no significant differences can be seen between LLM and SLM. As Figure 1b has shown the difference between the minimum and maximum cost in LLM and SLM were significantly higher, which indicates that the diameter influences on the cost of LLM and SLM are higher than TLM. With regard to this, we can suggest that when the diameter of the felled tree is smaller than 40 cm, the most economical choice for the forest manager is the TLM, but when the diameter of the felled tree exceeds 40 cm they can also choose LLM or SLM, depending on other influencing factors. Also, LeDoux & Huyler (2001) reported that the cut-to-length system is unable to handle stems with a stump diameter larger than 60 cm.

The range of costs depending on skidding distances was significantly different in SLM (Fig. 1a). This leads to the suggestion that in short distances SLM is the best alternative, whilst for longer distances LLM or TLM is to be preferred. Furthermore, the result indicates that WD has no important influence on costs in all alternatives (Fig. 1c).

Conclusion

In time study, numerical data produces unsolvable contradictions and problems (Erler, 1984), hence researchers can benefit from logarithms to solve this problem. Despite the limited numbers of time study data (30, 31 and 41 turns in TLM, LLM, and SLM, respectively) we found a high ratio (91%) between numerical and logarithmic data.

The most important part of the harvesting operation is the logging operation. In this context, from an economical point of view, we could suggest suitable harvesting methods in ground-based cable skidders system in a mixed broadleaved mountainous forest. Our finding implies that TLM can apply for trees, whose diameters are less than 40 cm, if a tree's diameter is bigger than 40 cm suitable alternative can be LLM absolutely in longer skidding distance but for trees with the biggest diameter in short skidding distances, suitable harvesting method can be SLM.

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