Productivity and Time Consumption of Timber Extraction with a Grapple Skidder in Selected Pine Stands

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Abstract

This paper presents the results of the study on work time and productivity of the John Deere 548G-III grapple skidder operating in pine stands on flat terrain. The research covered three types of treatment: late thinning, removal cutting in openings and clear cutting in openings. The average skidding distance was between 120 and 250 m. In the clear-cut stands, a mean duration of a skidding cycle accounted for 12 minutes, while in the thinned ones it was longer, lasting ca. 16 minutes. The investigators performed an estimate of parameters of multiple regression models, which revealed dependences between:

⇒ *duration of skidding cycles and stand conditions, number of logs per load and skidding distance, and*

⇒ *productivity achieved in specific skidding cycles and the above-mentioned variables, as well as wood volume per load.*

The highest productivity within the productive work time of a skidder was recorded in the stand where removal cutting in openings was performed; it exceeded 14 $m^3 \times h^{-1}$. In other stands, the efficiency was lower, not greater than 9 $m^3 \times h^{-1}$. However, differences between the productivity achieved within the productive work time and that recorded for the work place time did not exceed 20%, which indicated that skidding operations in the stands under scrutiny were organised properly.

Keywords: timber skidding, work efficiency, modelling of work time, productivity

1. Introduction

The volume of timber harvested in Poland has significantly increased in the recent years: from 27 mil. m^3 in 2000 to nearly 38 mil. m^3 in 2013 (Central Statistical Office 2014), though no more than 10% of wood (ca. 4 mil. m^3) had been extracted using technologies based on innovative multi-operational forest machines (Karaszewski et al. 2013). In Poland, skidding of timber is mainly performed with the use of agricultural tractors, 3000 of which operate in Polish forests, and properly equipped forest tractors (skidder type) – ca. 1500 machines (Kocel 2013). With regard to skidders, cable models are predominant, although grapple skidders have proved to be considerably more efficient (Bembenek et al. 2011, Mousavi et al. 2013). Having knowledge of productivity of particular skidding means, operating under diversified conditions, is essential for an appropriate selection and respective matching of these machines with a certain type of forest stand to assure satisfactory financial results (Acar and Yoshimura 1997, Gallis and Spyroglou 2012, Giefing et al. 2012, Marčeta et al. 2014). One of the ways to achieve this goal is to describe the relations between the productivity of skidding operations and properties of the terrain where skidding works were performed (Horvat 2007), selected characteristics of stands under treatments (Ghaffariyan et al. 2013), skidding means employed (Kluender and Stokes 1994), and skidding distance (Naghdi 2005, Maesano et al. 2013).

In respect to Europe, semi-suspended skidding of timber is the most popular method, commonly engaged in the central and southern part of the continent

Table 1 Characteristics of the stands under investigation

Stand	A	B	C
Studied area, ha	14.8	2.6	4.7
Location – geographical coordinates	50°03'21"N 19°35'29"E	50°03'29"N 19°30'47"E	50°03'57"N 19°35'41"E
Type of habitat	Fresh upland deciduous forest	Fresh upland deciduous forest	Fresh mixed coniferous forest
Tree species composition	10 Pine (*Pinus sylvestris* L.)	10 Pine (*Pinus sylvestris* L.)	10 Pine (*Pinus sylvestris* L.)
Age, years	77	77	102
Stocking index	0.9	0.9	0.7
Crown closure	Broken crown	Open crown	Broken crown
Average diameter at breast height, cm / Average height, m	36/27	31/26	37/25
Large timber, $m^3 \times ha^{-1}$	430	188	225
Mean volume of harvested trees ± SD, m^3	0.65±0.23	0.63±0.14	0.81±0.19

(Gil 2000, Kocel 2013). Results of studies on productivity of skidding operations performed under these conditions have been published in many publications, referring to various felling treatments, such as: thinning (Kluender et al. 2007, Spinelli and Magagnotti 2012, Vusić et al. 2013), clear cutting (Zečić 2005, Kluender et al. 2008), or selective cutting (Sabo and Poršinsky 2005, Behjou et al. 2008). However, there are only few papers dealing with the efficiency of skidding operations performed in stands in various manners by one type of skidder. A better recognition of this issue would enable an identification of conditions, under which the skidder achieves the highest productivity level, and consequently, provides the most profitable economic outcomes.

This paper aimed to characterise the duration of a skidding cycle and the productivity achieved by a grapple skidder, the John Deere 548G-III in particular, operating in pine stands in various manners. To be more specific, the research goals covered:

⇒ characteristics of timber loads and skidding distance

⇒ characteristics of work time structure

⇒ characteristics of a skidding cycle duration, including the determination whether the impact of the manner of use of a forest stand on this variable is statistically significant

⇒ constructing a mathematical model that would enable an estimate of a skidding cycle duration

⇒ determining the productivity of a skidder operating in the stands under investigation and developing a mathematical model for work efficiency.

2. Materials and methods

2.1 Research area

The research was carried out in southern Poland, in forest stands where various types of treatments were performed: late thinning (stand A), removal cutting in beech undergrowth (stand B), and clear cutting in openings (stand C).

All the trial plots were located on flat terrain, 200–300 m a.s.l. The major features of the stands studied are listed in table 1.

2.2 Machines and technology engaged in logging operations

In the stands under analysis, timber was extracted in the long length system (LLS) (Pulkki 2004). Cutting

Fig. 1 Skidder equipped with a forest grapple observed during the investigations

Table 2 General technical specifications of the John Deere 548G-III grapple skidder

	Unit	Value
Weight	kg	10,750
Length	mm	6330
Width	mm	2640
Height	mm	3010
Engine – type, power	kW	Diesel, 98
Grapple – gripping area in closed position	m^2	0.7
Cable winch – cable length / pulling force	m/kN	50/156

down and delimbing of trees, which were felled in the direction opposite to the direction of skidding, were performed with the use of chainsaws. Longwood was extracted in the long tree system (LTS), using the semi-suspended skidding method. This method of skidding employed the John Deere 548G-III grapple skidder, equipped with a cable winch remotely controlled, as displayed in Fig. 1.

The major parameters of the skidder used for extraction in the studied stands are listed in Table 2.

The skidder was operated by one person. The operator approached the logs as close as possible to minimise the distance of hauling wood with a winch and facilitate forming loads using a grapple. The skidding operations were performed in autumn and winter, when the soil was dry or frozen, not covered with snow.

2.3 Measurements and calculations

During the skidding operations, a time study was carried out by means of a digital stopwatch, with the accuracy of 1 sec. The work time measurements covered durations of all operations that were recorded at the felling site, including:

⇒ travel without a load – relocation of a vehicle without a load from the landing to the felling site. The time measurement started at the moment when the skidder left the landing and entered the operational track. The time measurement ended when the skidder stopped at the first log designated for loading and hauling

⇒ forming a load – lifting logs with the use of a grapple (possibly, dragging a log to the skidder using a cable) and relocating between particular logs. The time measurement started at the moment when the skidder stopped at the first log, and ended when the entire load was lifted

⇒ skidding – travel with a load to the landing. The time measurement started when the skidder, fully loaded, set on its way to the landing, and ended when the entire load was deposited at the landing

⇒ log stacking – relocating logs deposited at the landing, with the use of a log stacker, to align the stacks. The time measurement started at the moment when the entire load was laid at the landing, and ended when the last log was aligned properly

⇒ aligning ground beams – placing ground beams at the landing in an appropriate manner to create a stack foundation for skidded logs

⇒ daily maintenance – activities connected with the preparation of the skidder for work before its launching, and refilling the fuel

⇒ delays – unblocking the cable on a winch drum;

⇒ breaks – time for meal consumption, physiological needs and rest for the skidder operator.

The work efficiency was calculated for the productive work time and the work place time, based on the Classification of Time in forest work study (Acuna et al. 2012).

Upon completing every skidding cycle, the load was registered to compute the wood volume and mass. A hauling distance of every load was determined with the use of the Garmin 64S GPS device. In the course of the indoor research, the volume and mass of timber extracted during every skidding cycle were calculated, as well as the basic descriptive statistics referring to volumes of individual loads, work times and productivity. For determining the mass of skidded timber in kilograms, the authors assumed, according to Tomczak and Jelonek (2014), that one cubic meter of freshly felled pine wood weighed 750 kg. The significance of differences in duration of skidding cycles in specific stands was determined using the variance analysis (Fisher's test), followed by the post-hoc *LSD* test. The multiple regression analysis was used to estimate parameters of the equations that described dependences between the duration of skidding cycles and the work efficiency, and the stand conditions under which the skidding operations were performed, selected features of loads and the skidding distance. Afterwards, the above-mentioned parameters were computed. The significance of particular independent variables was assessed by means of the Student's *t*-test, while the Fisher's test was used for the entire model. For determining the relative significance of certain properties of the model, standardised (normalised) *ß* (beta) coefficients of regression were assumed as a measure of weights, which enabled the

Table 3 Characteristics of skidder loads, skidding distances and work times within skidding cycles

Stand	Number of cycles		Mean	Sum	Minimum	Maximum	Standard deviation
A	78	Number of logs per load, pcs.	3.28	256	1	7	1.38
		Load volume, m^3	2.20	171.82	0.27	6.28	1.12
		Skidding distance, m	197	15,378	18	581	127.59
		Work times within skidding cycles, min.	16.1	1254	1.6	40.5	9.2
B	127	Number of logs per load, pcs.	3.66	465	1	5	0.60
		Load volume, m^3	2.95	374.50	1.55	4.61	0.65
		Skidding distance, m	246	31,350	53	456	98.43
		Work times within skidding cycles, min.	12.0	1532	3.4	19.1	2.3
C	121	Number of logs per load, pcs.	2.94	353	1	5	0.63
		Load volume, m^3	1.86	223.27	0.72	3.17	0.45
		Skidding distance, m	124	15,082	27	246	46.16
		Work times within skidding cycles, min.	11.5	1389	1.8	18.9	2.9

authors to compare factors with various units (Stanisz 2007). All the statistical analyses were performed using the Statistica 10 software.

3. Results

The time studies performed in the stands under scrutiny covered in total 80 h 2 min 9 s, of which 24 h 49 min 5 s in stand A, 33 h 0 min 58 s in stand B, and 28 h 12 min 46 s in stand C. Within this time, the skidder completed 326 skidding cycles and hauled 1074 logs with a total volume of about 770 m^3 and mass of about 577,500 kg. Detailed characteristics of loads of the skidder and skidding distances are gathered in Table 3.

The logs were transported to upper landings, situated close to the stands under investigation; therefore, in all the cases, the minimum skidding distance was

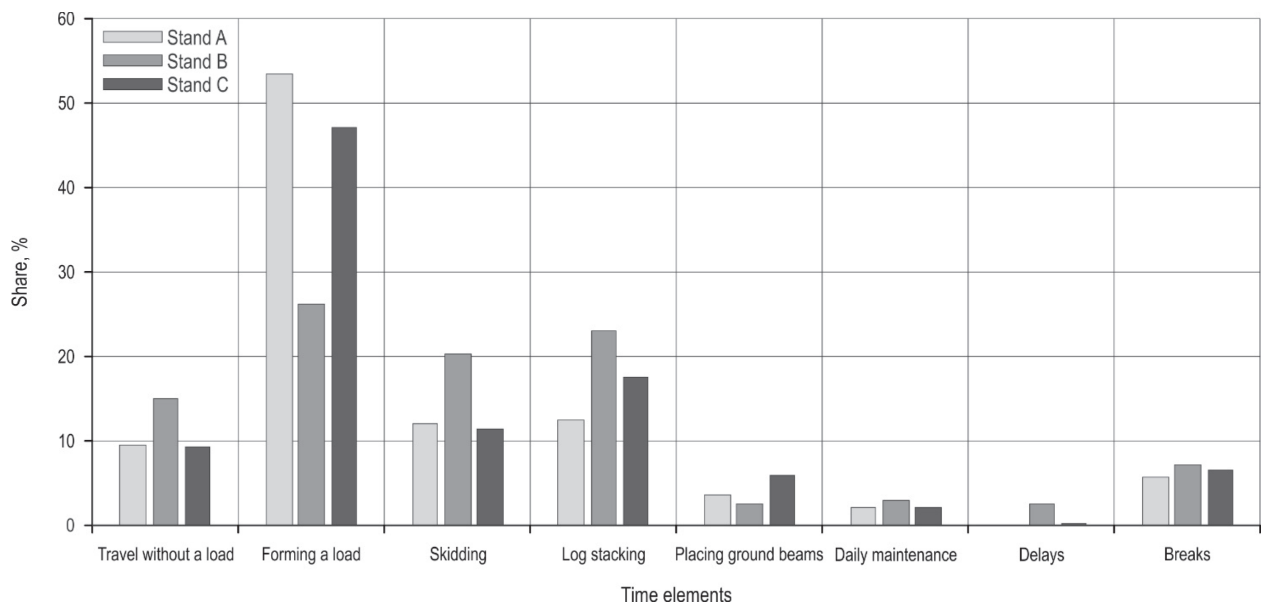

Fig. 2 Share of operations under analysis within work time

not excessive. The longest mean skidding distance was recorded in stand B, whereas, the shortest in stand C. In stands A and C, the mean volume of an individual load amounted to ca. 2 m^3, while in stand B this value accounted for nearly 3 m^3.

Fig. 2 shows the shares of particular elements of times within the work time. The diagram revealed legible differences between the stand B and the other two stands in terms of duration of most of the operations under analysis. Forming a load on this trial plot took slightly over 25% of the work place time and the times of skidding, travels without a load and log stacking had higher shares. In stands A and C, the time of forming a load was predominant, taking nearly 50% of the work place time. What is noteworthy is the surprisingly low, not exceeding 8%, share of times of breaks. Delays that occurred during the logging operations were not serious and they were fixed by the skidder operator as they emerged, due to which their impact on the course of works was insignificant. The share of the time of repairs was low, ranging from 0.16% in stand C to 2.5% in stand B.

Table 3 also contains characteristics of skidding cycles, enclosing the times of forming a load, skidding, log stacking and travels without a load (returns).

Variance analysis revealed statistically significant differences in mean duration of a skidding cycle between the stands under investigation (p=0.00; F=21.34). The *LSD* test proved that the differences between stand A and the other two stands (B and C) were significant. Dependences between the skidding cycle duration and the type of a felling site (stand), the skidding distance and the number of logs per load were displayed by means of the multiple regression model (Eq. 1), the parameters of which are presented in Table 4.

Table 4 Regression analysis – duration of a skidding cycle

Equation parameters: R=0.86; R^2=0.73; $R^2_{revised}$=0.73; F=221.82; p<0.001; Estimation error = 2.82					
Parameters of independent variables:					
	β	Standard deviation	Coefficients of regression	t	p
Absolute term		0.68	1.23	1.79	0.04
a	–0.59	0.41	–6.63	–15.90	<0.001
b	–0.12	0.42	–1.39	–3.25	0.01
c	0.43	0.19	2.60	13.43	<0.001
d	0.62	0.01	0.03	17.49	<0.001

$$\text{Skidding cycle duration} = 1.23 - 6.63 \times a - 1.39 \times b + 2.60 \times c + 0.03 \times d \pm 2.82 \text{ (min.)} \quad (1)$$

Where:

a zero-one variable of the stand category, taking the value »1« for stand B, and »0« for the other two stands

b zero-one variable of the stand category, taking the value »1« for stand C, and »0« for the other two stands

c number of logs per load (pcs.)

d skidding distance (m).

The model of multiple regression function presented above explained the variability in duration of skidding cycles well, which was reflected by the value of coefficient of determination R^2, accounting for 73%. The values of β coefficients obtained in the analysis indicated that the skidding distance had the greatest impact on the skidding cycle duration, followed by the stand-related factors – the conditions encountered in stand B and the number of logs per load. The factors with the weakest influence on the skidding cycle duration in the above-mentioned model were the conditions under which the wood was hauled in stand C, where the mean duration of a cycle was the lowest.

The values of productivity per hour achieved by the skidder studied, operating in particular stands, are displayed in Fig. 3.

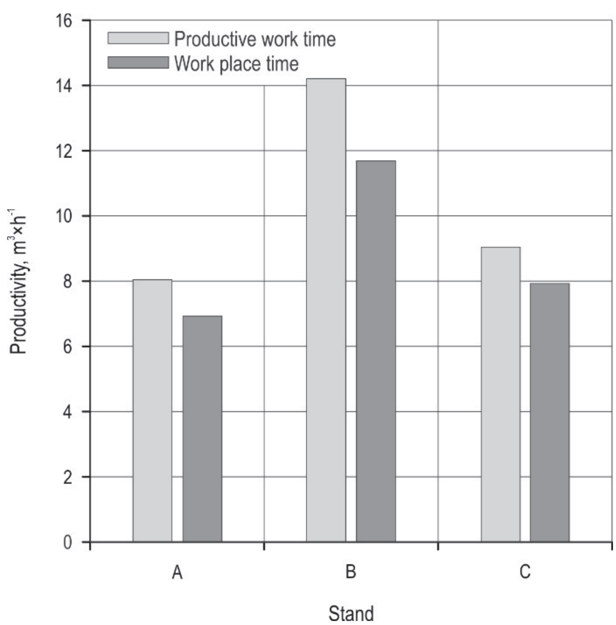

Fig. 3 Skidding productivity achieved in particular stands

The skidder achieved the highest productivity in stand B; it exceeded 14 $m^3 \times h^{-1}$ when calculated within the productive work time. On the other two trial plots, the productivity of skidding ranged from 8 to 9 $m^3 \times h^{-1}$. The differences in productivity achieved within the productive work time and the work place time of a working shift were not large, which might indicate that the logging operations were well organised and executed.

The model of multiple regression (Eq. 2), describing the efficiency of skidding cycles within the productive work time, took the form presented below:

$$\text{Productivity of a skidding cycle} = 14.79+3.72\times a-1.79\times b-2.73\times c-0.03\times d+5.08\times e\pm 4.53\ (m^3\times h^{-1}) \qquad (2)$$

Where:

e wood volume per single load (m^3)
other symbols as in equation 1 above.

Characteristics of the above mentioned model are presented in Table 5.

Table 5 Regression analysis – productivity of a skidding cycle

Equation parameters: R=0.73; R^2=0.53; $R^2_{revised}$=0.52; F=71.47; p<0.001; estimation error = 4.53					
Parameters of independent variables:					
	β	Standard deviation	Coefficients of regression	t	p
Absolute term		1.03	14.79	14.36	<0.001
a	0.30	0.65	3.72	5.66	<0.001
b	–0.14	0.64	–1.79	–2.79	0.01
c	–0.41	0.38	–2.73	–7.22	<0.001
d	0.73	0.01	–0.03	–11.77	<0.001
e	–0.57	0.44	5.08	11.47	<0.001

The model in question explained the variability in productivity of skidding cycles in slightly over 50%. The *F* test revealed that the model was statistically significant, though there must have been other independent variables that affected the productivity of skidding in its successive cycles. The values of standardised β coefficients of regression indicated that the skidding distance had the strongest impact on productivity, followed by the wood volume per load and the number of logs per load. Stand-related factors affected the productivity of skidding less significantly.

4. Discussion

Productivity of skidding means used for semi-suspended skidding of timber is highly diversified (Mederski et al. 2010). It depends on many factors, among which the most important are the following: the volume of extracted trees, number of logs per load, skidding distance, landform and atmospheric conditions, experience of an operator (Gil 2000, Ozturk and Senturk 2010, Sowa and Szewczyk 2013). Therefore, in the existing literature there are publications reporting both, the higher and the lower levels of skidding efficiency when compared with those presented in this paper; the latter did not exceed 14.2 $m^3 \times h^{-1}$, when calculated within the productive work time. For instance, Bembenek et al. (2011) stated that in a 140 year old clear-cut beech stand, the productivity of skidding performed by the HSM 904D grapple skidder, over a distance of 200–300 meters, was very high, accounting for 18 $m^3 \times h^{-1}$ within the productive work time. However, transport operations took place in a finely accessible area, the landform of which was only slightly inclined, with a dense network of skid roads. In comparison, the HSM 94 grapple skidder operating in the poplar and pine plantations, though on gently descending slopes, and hauling logs over the similar distance (220–285 m), achieved the productivity hardly exceeding 7 $m^3 \times h^{-1}$ (Mousavi et al. 2013). Whereas in higher mountainous locations, the MB Trac 900 skidder, operating on steep slopes in winter, reached the productivity of merely ca. 6 $m^3 \times h^{-1}$ (Acar and Dinc 2001). Nevertheless, logging operations in the mountains do not necessarily have to be less efficient as proved by other authors. According to Behjou et al. (2008), who analysed skidding of hardwood (beech and alder), performed down the slope with a 30% angle of inclination, over a distance of 300 meters, using the Timbejack 450C skidder, recorded that the machine managed to achieve the productivity of 22 $m^3 \times h^{-1}$. A skidder of the same type, operating under very similar conditions (in beech and alder stands, down the slope with a mean inclination accounting for 30%), over a distance of 900 meters, achieved only slightly lower productivity of 20.1 $m^3 \times h^{-1}$ (Lotfalian et al. 2011).

In the studies presented in this paper, the skidding distance accounted for 250 meters. According to Zečić et al. (2010), an increase in the distance of skidding performed by a skidder from 200 to 1000 meters would result not only in a decrease in efficiency by ca. 50%, but also in higher unit costs, which might even grow by 60%. However, skidding over shorter distances would not affect the productivity so strongly; according to simulations presented by Di Gironimo et al. (2015), extending a distance of semi-suspended skidding from 50 to 200 meters would lower its efficiency only by ca. 5%. Thus, it may be assumed that hauling operations in the stands studied were performed within optimal distances, which allowed the skidder to achieve a satisfactory level of productivity.

One of the factors that might have influenced the productivity recorded was the volume of individual loads. The operator of the John Deere skidder under analysis did not make a full use of the available capacity of the machine. The volumes of loads quoted in this paper ranged from 1.8–2.9 m^3 and they were closer to those recorded in young plantations, where volumes of loads oscillated around 2.2 m^3, at a mean volume of a single tree smaller than 0.4 m^3 (Mosuavi et al. 2012), rather than to clear-cut stands, where an average load contained nearly 6 m^3 wood (Mederski et al. 2010). Nevertheless, it is difficult to forecast how the efficiency of skidding would change if the skidder operator formed larger loads, as this operation took the most of time (up to 50%) on all the trial plots under investigation. Adding more logs to a single load would even increase the share of this work time elements. The stands where skidding took place were not optimal in terms of employing a grapple skidder, which proved to be much more effective while operating on large clear-cut sites. With regard to the latter, the time of forming loads would also be the shortest. However, the studies presented in this paper were carried out in pine stands under thinning and complex felling system, which are typical of Polish forest management. The share of time of forming loads was similar to the data reported in the existing literature only in stand B. Mosuavi et al. (2013) stated that this time element was prevalent in a semi-suspended skidding cycle, and constituted 27% of work time for a grapple skidder, while its share for a cable skidder reached 36%. Sabo and Poršinsky (2005), having analysed skidding performed in the mountains, on slopes of various angles of inclination, estimated that depending on the particular stand, the share of time of forming loads ranged from 30 to 32% within the total time of work.

In the clear-cut stands (B and C), the mean duration of a skidding cycle was the same (the differences detected appeared to be statistically insignificant), and accounted for ca. 12 minutes, which corresponded to similar values quoted in the existing literature. According to Mederski et al. (2010), who conducted studies in a clear-cut beech stand, the mean duration of a skidding cycle accounted for 10.9 minutes. In the thinned stand A, this time was longer (ca. 16 minutes), though it was within the range given in the related literature. Admittedly, Brinker et al. (1996) reported that the mean duration of a skidding cycle performed in pine plantations, with the use of the Timberjack 240C grapple skidder, over a distance of 300 meters, amounted to 5 minutes. On the other hand, according to Zečić et al. (2010), the mean duration of a skidding cycle over the same distance, employing the Timberjack 240C skidder, though performed in fir and beech stands in the mountains, lasted 35 minutes.

Due to a great number of variables determining the duration of skidding and its productivity, a multiple regression analysis is often used for modelling these properties. This research covered an elaboration of models that described the duration and the productivity of skidding cycles within the productive work time, based on a skidding distance, number of logs per load, and wood volume per load. Those variables were used for developing an efficiency model. The models also included other variables defining the treatment performed and stand conditions encountered on a certain felling site. The latter is a variable hardly ever used for modelling of work time and productivity, which is mainly due to the fact that studies on productivity of skidding are usually conducted in stands managed within only one category of felling system. Nevertheless, the field research discussed in this paper was carried out in three stands managed within different felling systems, which enabled the authors to include the variable in question into modelling. A similar approach was taken by Nurminen et al. (2006), whose model of skidding efficiency included, among others, a variable describing the type of cutting. The variables most commonly used in models published in the existing literature referred to the number of extracted logs or load volume and skidding distance (Bolding et al. 2009, Borz et al. 2013, Vusić et al. 2013), in some cases complemented with the inclination of the terrain (Zečić and Marenče 2005, Gholami and Majnounian 2008, Ozturk and Senturk 2010), the number of loads (Ozturk 2010), type of skidder (wheeled, crawler) (Maesano et al. 2013) or temperature and soil conditions at which logging operations took place (Horvat et al. 2007). Borz et al. (2014), apart from the variables mentioned above, developed their models of duration of skidding operations, which included the skidding direction, down or up slope. Upon modelling productivity of logging operations based on wide-spread research conducted in North America, Goychuk et al. (2011) suggested to complement these models additionally with a few variables, such as: season of the year, technological system and human factor related to the manner of work performance and experience of a particular operator of the skidder.

5. Conclusions

The John Deere 548G-III grapple skidder, performing skidding of longwood in pine stands, achieved a satisfactory level of productivity and, therefore, the authors recommend to engage machines of this type for skidding under conditions in question, in particular, in clear-cut pine stands. Logging operations in thinned stands, where a skidder is forced to maneuver among trees remaining in the stand, are expected to be less efficient. Therefore, an essential role in forest stands within younger age classes is played by a properly designed and, what is even more important, suitably utilised network of forest tracks.

The models of multiple regression obtained in this studies, defining the productivity and the time consumption of skidding, may appear very useful in practice since they enable relatively reliable estimate of productivity of logging works, performed not only in stands like those studied, but also in stands with varying conditions, partly similar to those discussed in this paper (Papyrakis and Gerlagh 2007). Taking into account an extremely vast incidence of pine species in Europe and Asia (Sinclair et al. 1999), the aspect of studies presented here appears to be very significant.

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