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Efficiency of slash bundling in mature coniferous stands

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The biomass of forests is one of the oldest and most popular sources of renewable energy. Aside from round wood, logging residue is also being used with increasing frequency to produce energy. Under European conditions, the most frequently implemented technology of using logging residue is chipping, either directly at the cutting site or at the forest roadside. However, for over a dozen years now, with more and more success, solutions have been implemented which make it possible to compress the biomass into bundles. The aim of this study was to estimate the work efficiency of a John Deere 1490 bundler working in clear cuts with various degrees of material preparation. The structure of a working day, work productivity rates, as well as cost and energy consumption were determined for each of three variants. The effectiveness of using a bundler, expressed by the productivity achieved, depends largely on the extent the wood slash is prepared. When the slash is concentrated in rows or piles, the machine does not have to travel over the entire work area to gather scattered material, which increases work efficiency by about 25 to 30%. The obtained values relevantly affected costs and the amounts of energy consumed.

Key words: Renewable energy, forest biomass, slash bundler, time study, energy use.

INTRODUCTION

The intense social and economic progress observed in many different parts of the world has contributed to a growing interest in various types of energy carriers. It is estimated that during the next thirty years, the demand for energy will grow by 30%, and even by about 60%, in developing countries (The Outlook for Energy, 2012).

In view of the fact that access to fossil fuels is limited, renewable energy sources (RES) are being especially intensively promoted in recent years. The possibility of utilizing this type of energy source is determined by its common availability and the relatively low cost of its conversion into energy. Promotion of utilizing RES allows the diversification of supply sources to be increased and creates favourable conditions for the development of distributed energy generation based on locally available raw materials.

A comparatively large amount of biomass assigned for the above discussed purposes can be obtained from forests. This refers to round wood characterized by low technical quality, small-sized wood, and logging residues. Under Polish conditions, the potential amount of biomass is estimated at 3-5 Mio. m^3 of wood per year, depending on the adopted scenarios taking into account such factors as the estimated amount of obtained wood, volume of tree biomass and the volume of slash not presently utilized for economic reasons (Płotkowski, 2007).

Until 2004, the most commonly implemented method of using logging residues was burning them directly on the ground after having previously turned thicker branches into fuelwood. Despite the simplicity of this activity, the process of burning had a negative impact on the environment in comparison to other methods (Sadowski et al., 2012). Intense development of technologies for energy acquisition from forest biomass has provided

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Table 1. Parameters of bundles produced by different bundling machines (Chlebowski and Jabłoński, 2012).

Parameter	Woodpac Enfo 2000	Fixteri Baller	Flexus Tornado	Pinox 828/830	John Deere 1490D
Length [cm]	240-300	260-270	135	260-350	230-250
Diameter [cm]	60-80	80	125	70-80	50-80
Weight [kg]	400-600	300-450	300-350	400-650	300-700
Binding method	twine	twine	netting	twine	Twine
Work efficiency [bundles/h]	20-25	7-12	20-25	20-25	25-30

conditions facilitating the use of logging residues on an industrial scale. One of the possible solutions is bundling.

Nowadays, more and more frequently, large heat generating plants, as well as heat and power generating plants, are willing to accept biomass. What is more, such plants are interested not only in wood, but also in logging residues. The use of logging residues, just as it was previously with the unsellable parts, sizes and species of trees, has become an attractive way to increase energy production from forest biomass. The Scandinavian countries were pioneers in the systematic large-scale use of forest residues (Hakkila and Parikka, 2002; Kärhä and Vartiamäki, 2006).

The most common supply chain in Scandinavia and Central Europe is based on chipping the raw material at the roadside (Yoshioka et al., 2006; Stampfer and Kanzian, 2006; Eker, 2011; Röser et al., 2012). Chipping can also take place directly at the logging site, in the terminal or at a heat generating plant.

For a dozen or so years, the bundling of logging residues has been applied with growing success. This technology is among the most modern of solutions. It should be noted, however, that most installations for energy production require supplies of raw material in the form of chips because they are easily portioned and facilitate the control of processes considerably. This is also the case with bundles. Due to logistic reasons, the choice of a proper technological process of wood harvesting for energy purposes depends on a number of factors. They include the following: wood harvesting system, work conditions, cutting categories, degree of integration of the process of logging residue acquisition with the process of round wood harvesting, and the operator's experience (Jodłowski, 2004).

The bundling of logging residues is especially popular in Scandinavian countries. The bundling method offers operational and logistic advantages. A major advantage of the bundling system is that the same handling and administrative routes can be used as in conventional round wood logging and transport. Another advantage is the possibility of storing bundles at all stages of the production chain (Parikka et al., 2005; Johansson et al., 2006; Zychowicz and Sosnowska, 2007).

Several types of bundling machines are produced worldwide. However, most solutions are based on the technology developed by the Timberjack Company (presently known as John Deere due to business ownership transference). Table 1 provides a list of currently manufactured bundling machines and the characteristics of the bundles they produce.

Logging residues are bundled into cylindrical bundles in log-like units. The bundling method can be divided into three phases. In the first, collected logging residues are pressed by feeder rolls. Then the compacting continues in a rectangular presser. The last compacting phase ends with the tying of the pulse-fed logging residue bundle. Finally, bundles are cut into the desired lengths with a chain saw (Parikka et al., 2005).

In a majority of cases, studies on bundling machines have concentrated on analyzing their work efficiency (Cuchet et al., 2004; Rummer et al., 2003; Vonk and Theunissen, 2007). They focused on such machines in which the operating device was mounted on a forwarder. In locations where the terrain conditions made it possible, the machines were moved directly to a cutting site. In the case of mountain forests, in areas with steep terrain, the machines could not be brought to the immediate proximity of the cutting site. In such locations, the process of wood harvesting relied on cable yarders. Wherever that solution was implemented, logging residues were accumulated at roadside landings and truck-mounted bundlers were utilized for their bundling (Kanzian, 2005; Lindroos et al., 2010; Spineli et al., 2012).

Forest utilization in accordance with the rules of sustainable forest management requires that forest biomass harvesting be implemented by using a technology having minimal impact on the environment. There are many methods, of greater or lesser complexity, which allow such an effect to be assessed. One of the methods is the Life Cycle Assessment (LCA – ISO 14040-2), which constitutes the foundation for an evaluation based on an energy audit (Yoshioka et al., 2006; Våg et al., 2000; Lindholm et al., 2010; Klvač, 2011). The bundling operation is crucial from the point of view of energy consumption of the entire chain of forest biomass supply, from the moment the raw material is produced to the moment it is brought to combustion in the heating plant.

The aim of the present study is to analyze the work

Table 2. Characteristics of research plots.

No	Variant	Forest site address	Area [ha]	Species structure of the stand			Harvested volume [m³/h]		
				Birch	Scots pine	Spruce	Large-size wood	Medium-size wood	Logging residues
1	V1	01-30-2-15-225	2.66		54.4	45.6	278.34	138.42	59.21
2	V1	01-30-2-15-340	2.43	2	63.4	34.6	211.37	89.72	22.41
3	V1	01-30-1-06-151	2.53	1.8	87.7	10.5	213.32	51.62	47.43
4	V1	01-30-1-06-157	2.11	0.4	91.5	8.1	310.45	70.71	24.88
5	V1	01-30-1-06-161	1.92		96.4	3.6	264.59	45.95	22.79
6	V1	01-30-1-06-163	3.19	1.1	92.4	6.5	264.23	76.45	32.92
Average				**0.88**	**80.97**	**18.15**	**257.05**	**78.81**	**34.94**
7	V2	01-30-1-06-165	2.26		91.2	8.8	187.15	75	39.82
8	V2	01-30-2-12-299	3.78	5.2	42.6	52.1	135.05	82.81	46.3
9	V2	01-30-2-13-312	2.91	0.8	49.8	49.4	127.17	52.59	24.05
10	V2	01-30-2-13-312	1.42		11.5	88.5	169.26	94.42	24.65
11	V2	01-30-2-13-331	1.67	3.2	17.2	79.6	187.75	102.35	41.92
12	V2	01-30-2-15-224	3.04	0.2	68.5	31.3	279.09	127.16	31.59
Average				**1.57**	**46.80**	**51.62**	**180.91**	**89.06**	**34.72**
13	V3	01-30-2-15-226	2.46	0.3	68.8	30.9	184.63	70.26	36.06
14	V3	01-30-2-15-244	1.14		30.7	69.3	207.72	98.9	60.96
15	V3	01-30-2-15-340	1.09	2	44.9	53.1	239.55	111.62	25.14
16	V3	01-30-1-06-154	0.84	2.8	92	5.2	217.92	34.94	41.67
17	V3	01-30-1-06-154	1.23		99.9	0.1	249.3	28.19	28.46
18	V3	01-30-1-06-154	0.9		95	5	305.13	40.08	38.89
Average				**0.85**	**71.88**	**27.27**	**234.04**	**64.00**	**38.53**

efficiency of a forwarder-mounted bundler in mature coniferous stands. The study takes into account not only the parameters related to work efficiency and the cost of machine usage, but also some of the aspects related to energy consumption in the course of the entire operation.

MATERIALS AND METHODS

The John Deere slash bundler 1490D was the subject of the study. The basic unit of the bundling device was an eight-wheel forwarder, powered by a John Deere 6068 HTJ/136 kW engine. The total mass of the entire machinery set amounted to 23,000 kg. The bundling components were operated through the hydraulic crane of the forwarder.

Study site

The study area was located in north-eastern Poland and comprised 18 selected plots. Their detailed characteristics are provided in Table 2. All research plots contained coniferous stands, dominated by Scots pine with varying proportions of Norway spruce and scattered birches.

Process variants

It should be taken into account that bundling is one of the important elements of the supply chain. Delivering forest biomass to the end-user requires undertaking a number of successive technological and transport operations, including activities related to the harvesting, forwarding and haulage of biomass. These operations can be conducted directly in the forest, at specially prepared collection terminals, or in energy generating plants. The possible solutions for the analyzed variants are shown in Figure 1.

It was decided that the study would be conducted in three variants. The first variant (V1) focused on the areas where timber harvesting was performed in a traditional manner, using a chain saw. Logging residues were evenly distributed over the area and not accumulated. The next two processes were related to fully mechanized timber harvesting. In the second variant (V2), the residues were mechanically raked into rows, whereas in the third variant (V3), the trees were cut in such a way that after several trees had been processed it was possible to gather the residues into a pile.

Indicators of the efficiency of the processes

The efficiency of the bundler was estimated on the basis of field measurements conducted in selected plots. These lasted for one working day (ca. 8 h) in each of the plots. This meant that results relating to particular variants were based on measurements conducted for six days. The structure of a working day, work efficiency, direct hourly cost and unit cost were analyzed, as well as the amounts of energy used in the process.

The structure of the working day was based on the method of

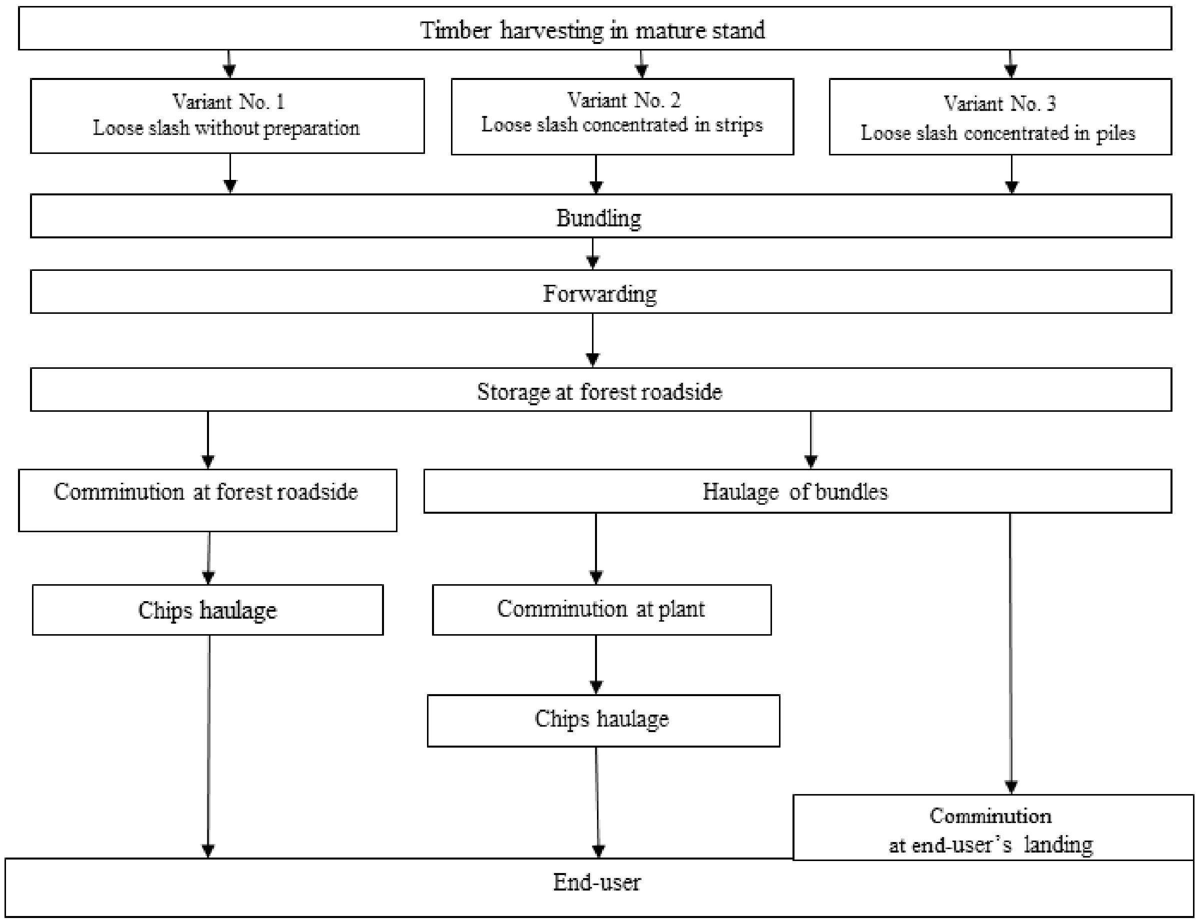

Figure 1. Possibilities of bundled slash supply chains.

continuous time measure. The method was implemented with the aid of a portable PSION computer with TIMER software. Outlining the structure required dividing the working day into particular time fractions. In order to do this, a working shift was divided in the following manner:

$$T = T_1 + T_2 + T_3 + T_4 + T_5 \quad \text{(h)} \qquad (1)$$

where:

T -Duration of the shift (h);

T_1 - Loading (beginning with logging residues collected from the forest floor and lasting until the moment when a residue bunch was lifted and placed on the feeding table) (h);

T_2 - Bundling (time elapsed between the moment the machine started to compact residues, and the moment when the individual bundle was tied with twine) (h);

T_3 - Cutting (time elapsed between the moment a chain saw started to cut off the bundle, and the moment when it dropped off) (h);

T_4 - Driving (time when the bundler was moving from one spot to another) (h);

T_5 - Delays (time devoted to maintenance, servicing the machine, and personnel breaks) (h).

The work productivity rate, expressed by the number of bundles/h, was estimated for each hour separately on the basis of the number of produced bundles.

Direct hourly costs were calculated with the aid of the software program "The Machine Cost Calculation – Business Model", which was developed for the Cost Action FP0902 Project "Development and harmonization of new operational research and assessment procedures for sustainable forest biomass supply" and specifically as part of WG3's mandate. Unit costs, expressed as €/m^3, were calculated by dividing hourly costs by the obtained hourly work efficiency value. The average volume of one bundle equaled 0.9 bulk cubic meter. The conversion coefficient of a solid cubic meter (m^3) equaled 0.4.

Energy consumption during the bundling process was estimated by taking into account not only the wear and tear of the materials of machine use, but also the energy required for its manufacture. The total energy expended in production and use of forest machines in the course of their operation, according to the LCA analysis, was calculated per m^3 of obtained biomass with the following formula (Lindholm et al., 2010 with modification):

$$E_m = \frac{1.2(0.85E_s M + 0.15E_g M + E_p M)}{\mathrm{LW_p}} \quad (\mathrm{MJ/m^3}) \qquad (2)$$

where:

Table 3. Average structures of working days and time consumption per 1 bundle in analyzed variants.

Structure	Variant I			Variant II			Variant III		
	h	%	min./bundle	h	%	min./bundle	h	%	min./bundle
T1 - Loading	3.43	44.20	1.74	2.96	36.80	1.06	2.69	31.50	0.87
T2 - Bundling	1.88	24.30	0.96	2.81	34.90	1.00	3.28	38.40	1.05
T3 - Cutting	0.29	3.70	0.15	0.36	4.50	0.13	0.41	4.80	0.13
T4 - Driving	0.94	12.10	0.48	0.60	7.40	0.21	0.87	10.20	0.28
T5 - Delays	1.22	15.70	0.62	1.32	16.40	0.47	1.29	15.10	0.41
Total	7.75	100.00	3.95	8.05	100.00	2.88	8.53	100.00	2.75

E_s – energy consumed during steel manufacture (MJ);
E_g – energy consumed during rubber manufacture (MJ);
E_p – energy consumed during machine production (MJ);
M – mass of the machine (Mg);
L – lifetime of the machine (h);
W_p – work efficiency (m^3/h);
1.2 – correction coefficient related to machine servicing (determined based on data provided by the machine servicing company indicating that the spare parts required during the entire time of using the machine equals 20% in relation to the weight of the entire machine).

Machine production was considered in terms of two issues: raw material required for production and the manufacturing process. It was assumed that forest machines consisted of 85% metal and 15% rubber and plastic (Athanassiadis et al., 2002). Energy consumption accompanying steel production amounted to 20.6 MJ/kg. Energy outlay equal to 2.0 MJ/kg had to be added to the above value as required for iron ore mining. For gum products, ca. 23.4 MJ/kg is needed. Furthermore, machine production also had to be taken into account while analyzing energy consumption. In the case of forest machines, this amounted to 14.6 MJ/kg.

It was assumed that such oil products as: grease, hydraulic fluids, gear oil and engine oil had the same properties as diesel fuel. The following fuel characteristics (IPCC, 2006) were applied in the calculations: diesel fuel – heat of combustion (43.33 MJ/kg), fuel density (0.83 kg/l). The energy consumed during the production of diesel fuel was reported to equal ca. 4.5 MJ/l (Klvač et al., 2012). The achieved results were analyzed using the ANOVA test in order to find significant differences amongst the various factors. The differences between variants were assessed with Tukey's test.

RESULTS

The amounts of biomass obtained from slash per ha ranged between 22.41 and 60.96 m^3. Average values for particular variants were similar, ranging from 34.72 to 38.53 m^3/h. The share of Scots pine and Norway spruce differed from one variant to another. It should be noted that in the case of stands composed solely of pines, problems occurred with retaining the form of bundles. Sometimes they broke as they fell to the ground. An admixture of spruce trees in the stand resulted in stiffer bundles.

The average working time of the machine differed slightly between particular variants. As shown in Table 3, it ranged from 7.75 to 8.53 h. In variant I, where the logging residues were scattered, the most time (44.2%) was taken up by forming the load and feeding. In the other two cases, the amount of time needed for this was smaller and amounted to 36.8 and 31.5%, respectively. A significant portion of time was also taken up by the process of bundle formation (T2), which consisted of placing the residues onto the feeding table and then sweeping them towards the system of forming presses. A formed bundle was ca. 70 cm in diameter. Then the bundle was tied up with plastic twine; ca. 60 m of twine was used per bundle. When a bundle of proper length (2.4 m) was produced, it was cut off with a chain saw (T3).

Although the observed percentage differences between T2 times were considerable, ranging from 24.3 to 38.4%, the amounts of time it took to produce individual bundles were comparable and ranged between 0.96 and 1.05 min. The times of bundle cutoffs were also similar in all cases and equaled 0.13 to 0.15 min. The fact that the raw material was widely scattered in the first variant required the machine to move across the site more times in comparison to the remaining two variants. The observed differences were significant. With respect to an individual bundle, the times required for this were 0.48, 0.21 and 0.28 min. for V1, V2, and V3 variants respectively. Delays included time required for technical maintenance, organizational breaks and breaks required by the machine operator whenever a rest was needed. Technical maintenance included minor repairs, as well as replacing the chain saw with a new one 3 to 4 times a day, that is, every time ca. 30 to 60 bundles had been produced. The frequency of such replacements depended mainly on how much the residues had been polluted, e.g. with sand, during the mechanical collection of the material. Furthermore, the operator had to grease the head 2 to 3 times during a work shift. Finally, technical maintenance also included the time required for fuel refills, which had to take place after the production of every 130 to 150 bundles.

Figure 2 shows average work productivity for the analyzed variants. The highest productivity was observed in the variant where the residues had been gathered into piles prior to bundling. In this case, the average productivity was 21.85 bundles/h. In the variant where the

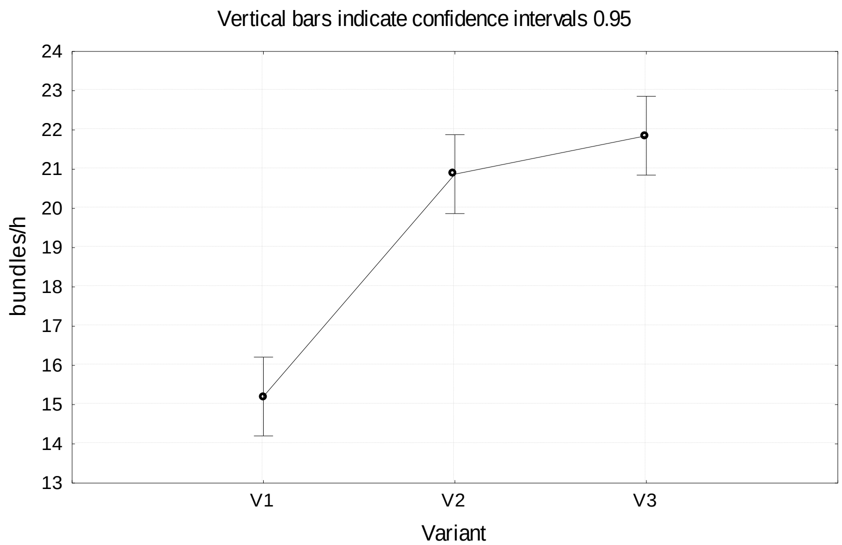

Figure 2. Average efficiency of the work of slash bundlers for specific variants.

Table 4. Results of testing the significance of the differences between average work efficiency and energy use of the variant processes.

Parameter	SS Result	df result	MS result	F	P
Bundles	1235.79	2	617.90	49.866	0.0000
MJ/m^3	31572	2	15786	48.174	0.0000

Table 5. Tukey's honest significance test – average work efficiency.

Variant	Average mean	1	2
V1	15.21		****
V2	20.87	****	
V3	21.85	****	

residues were scattered, work efficiency equaled 15.21 bundles/h. Furthermore, it was stated that there were statistically significant differences between efficiency levels achieved in particular variants (Table 4). Tukey's test revealed the existence of two homogeneous groups (Table 5). The first of these consisted of variants II and III. Variant I, due to the much lower productivity rate, was classified as belonging to a separate group.

The hourly cost had to be calculated in order to specify the amount of the direct unit cost. The input data required for these calculations are presented in Table 6. After the relevant data were taken into account, the cost was calculated to equal 78.81 €/h (103.16 USD/h). The amounts of unit costs were obtained by dividing this amount by the obtained average work productivity of particular variants (V1 – 5.48 m^3/h; V2 – 7.51 m^3/h; V3 – 7.87 m^3/h). Those amounts were as follows: 14.39 €/m^3 (18.84 USD/m^3) for V1, 10.49 €/m^3 (13.73 USD/m^3) for V2, and 10.02 €/m^3 (13.11 USD/m^3) for V3. On the basis of the above calculations, it could be concluded that having a harvester gather the logging residues in piles of appropriate sizes was most advantageous from an economic point of view. Then the bundler could produce a comparatively large number of bundles without moving away from a particular location.

Table 6. Cost calculation for the slash bundler.

Machine	John Deere 1490D
Input data	
Purchase price (€)	420,000
Salvage value (%)	10
Expected Economic Life (h)	20,000
Interest rate (%)	8
Machine insurance (€)	1500
Fuel cost (€/l)	1.3
Fuel consumption (l/ h)	11
Oil and lubricant cost (% of fuel costs)	20
Maintenance and repair cost (%)	60
Total tyre set cost (€)	12,000
Estimated tyre set life (h)	14,000
Number of shifts	1
Basic wage of operator (€/h)	7
Output data	
Fixed costs (€/h)	32.09
Variable costs (€/h)	30.80
Operator costs (€/h)	8.75
Total costs (€/h)	78.81

1 EUR (€) = 1.3090 USD (March 2013).

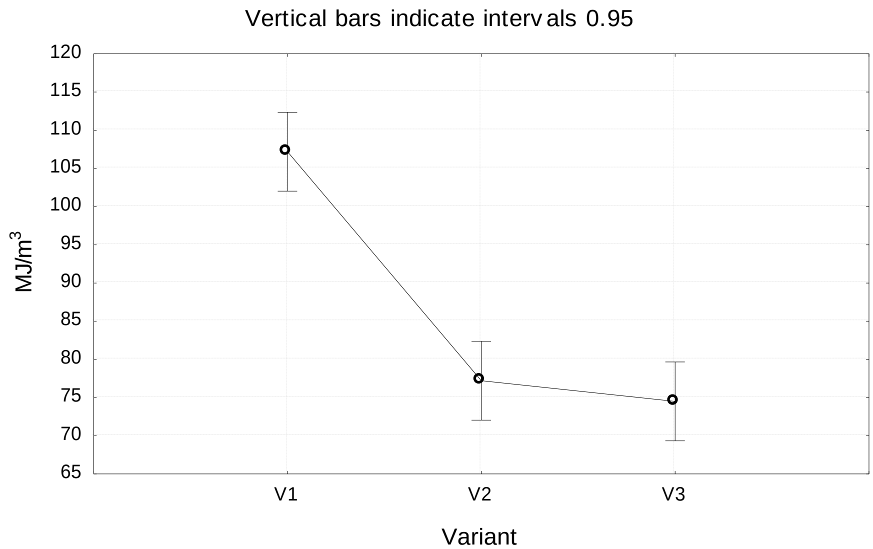

Figure 3. Average energy use of slash bundling for specific variants.

An important element of evaluating the processes, especially the ones related to producing the raw materials for energy, is to specify the amount of energy outlay to be consumed. In the case of the analyzed machine, this energy consumption amounted to 563.96 MJ/h. The following data were adopted with reference to fluids consumption: hydraulic fluids: 300 l per 1000 h; gear oil: 150 l per 1000 h; engine oil: 24 l per 500 h, and grease for the chain saw: 3 l per 8 h. According to these calculations, the energy consumption needed to manufacture the machine equaled 51.50 MJ/h. In this case, most of the necessary energy outlays were related to fuel. Energy consumption during bundling differed from one variant to another. In the first variant it was the highest, amounting to 107.19 MJ/m^3 (Figure 3). Decidedly lower values were observed in the case of the second (77.21 MJ/m^3) and third variants (69.34 MJ/m^3).

As in the analysis of work efficiency, statistically significant differences were observed between the obtained values. Furthermore, Tukey's test has also revealed the existence of the same homogeneous groups.

DISCUSSION

The European market has recently expressed great interest in using logging residues for the purpose of energy production. Previously, this material was mainly used for many decades to produce small-sized wood, used by local communities for heating purposes. The remaining residue, such as small twigs and conifer needles, were crushed by specialized forest machines directly at the cutting site.

Loose logging residues are characterized by a relatively large volume in relation to mass. This results in specific logistics problems, making it ineffective to transport this material over longer distances. Compensatory measures were required, and hence the possible use of the bundler arose.

Its effectiveness depends on many factors. Without a doubt, these include terrain and tree stand conditions. The analyzed research plots were located in lowland areas and were comparatively easy for machines to access. All of them featured clear cuts, conducted mainly in tree stands where pines were prevalent.

The efficiency achieved during the study for specific variants reached between 15 to 22 bales per hour, which was mostly similar to results obtained by other authors, who conducted their research in lowland areas. As a rule, values did not reach more than 25 bales per hour. The compacting head in all these cases was mounted on the chassis of a forwarder (Rummer et al., 2003; Cuchet et al., 2004; Ghaffariyan et al., 2011; Liška et al., 2011; Jabłoński and Chlebowski, 2012).

Slightly less efficiency, from 8 to 14 bales per hour, is reached in mountainous terrain. This is due to the more difficult terrain conditions and the need to travel between the sites where logging residues were stored. Using a machine mounted on a forwarder incurs considerable relocation costs, which would often render the operation unprofitable. For this reason, heads mounted on a highly mobile truck are often used in such a situation (Stampfer and Kanzian, 2006; Spinelli et al., 2007, 2012).

The operator's proficiency was also important, as this could account for differences of up to 30% (Spinelli et al., 2012).

The values of the above discussed parameters determined the results of the remaining indicators, mainly unit costs and the energy consumption of the process. The hourly cost of using a machine such as the one under discussion was slightly lower in Poland in comparison to Western European countries or the USA due to the difference – 4 to 5 times - in the remuneration of the operators. According to Stampfer and Kanzian (2006), and Spinelli et al. (2012), the cost of utilizing a machine mounted on a truck amounted to ca. 160-180 €/h. It should also be taken into account that the existing differences in hourly costs could be due to different methodologies applied for their calculation.

The amount of unit cost is affected by the achieved level of work productivity. As has already been mentioned, sometimes the differences can be considerable, determining whether the implementation of a solution will be profitable or not. Another important factor, as has been confirmed by the conducted research, is how the logging residues are distributed prior to bundling. Whenever they are concentrated and not scattered over the plots, better results are achieved.

Any industrial activity is connected with an energy outlay. This is especially significant when converting a raw material for energy production. In the case of bundling logging residues, the values describing energy consumption considerably differ from one study to another. The values obtained during this study ranged from 69 to 107 MJ/m^3. These figures incorporate the calculation based on the LCA method, which takes into account the whole life cycle of a product, whereas others only accounted for the consumption of fuels. Thus, different values are given in the literature of the subject, ranging from 45 (Jabłoński and Różański, 2003) to slightly over 120 MJ/m^3. It should be noted that a decidedly greater proportion of the energy outlay is related to the use of fuels. Only about 10% pertains to the machine itself.

The bundling of logging residues is one of the elements of a logistics chain. The efficiency of the entire process, where bundling is one of the components, depends among other things on the good coordination of biomass harvesting, transport operations, as well as chipping and combustion.

Conclusions

1) The effectiveness of slash bundling, expressed by the obtained work productivity rate, largely depends on how the residues are distributed over the forest area. When they have been gathered in rows or piles, the machine does not have to move all over the work area to collect scattered material, which increases efficiency by 25 to 30%.

2) The economic effectiveness of the process depends on hourly costs, which in Poland is about 80 € h^{-1}, as well as achieved work efficiency. Variation in the hourly wage levels of machine operators in various countries has a significant effect on results.

3) The use of a slash bundler is related to a specific energy outlay. Calculated according to the LCA method, such an outlay amounts to 563.96 MJ/h, with 10% of the value relating to the machine itself, and the remaining 90% relating to the materials used in its operation. Unit energy consumption per m^3 of bundles amounts to 107.19 MJ in the variant where the raw material is scattered over the ground, and 69.34 MJ in the variant where it was concentrated into piles.

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