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Comparative Time Study of Conventional Cut-To-Length and an Integrated Harvesting Method—A Case Study

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Received: 15 February 2018; Accepted: 6 April 2018; Published: 9 April 2018

Abstract: Logging residues offer a significant contribution to the economical profitability and sustainability of forest-based resources. It is always desirable to optimise the harvesting and extraction method to improve the economy of the process along with ensuring sustainability from an environmental point of view. This study compares two harvesting methods, i.e., conventional cut-to-length (CTL) followed by harvesting residue extraction for energy and an integrated harvesting method combining CTL with harvesting residue pre-piling by the harvester followed by the extraction of both timber and logging residues for energy. The study was carried out in spruce stands *(Picea abies* (L.) Karst.) in South Moravia (Czech Republic) at Pozořice and Kuničky. Two methods utilized by harvesters and forwarders were compared. The first case was a conventional CTL method when trees are felled, delimbed, and cross-cut by the harvester. The resulting logs are pre-piled and then transported by the forwarder. In this case, the harvesting residues remain in the stand. The method does not involve utilizing harvesting residues such as brash mat on striproads but rather extracting them in an independent step as an energy source. In the second case, the resulting harvesting residues are piled up by the harvester to be later extracted by the forwarder. Such extracted harvesting residues are stored at the roadside for seasoning and future comminution. The aim was to obtain input data for internal analysis of a private entity contracting in a logging operation. The client demanded that the increase in time needed for the production of one timber unit with simultaneous harvesting residue preparation be measured. By our estimates, the integrated harvesting method required 33% more (harvester) and 16% less (forwarder) time compared to the alternate method for the extraction of harvesting residues, which in turn results in approximately 8% longer total operational time for the complete operation.

Keywords: CTL; harvester; forwarder; time study; harvesting residues; biomass

1. Introduction

Forests are an important carbon repository in terms of its global balance [1]. In the context of the Kyoto Protocol, it is necessary to consider forestry as a possible tool to mitigate the increase of greenhouse gases (GHG) in the atmosphere. However, every country has its own different strategies to address carbon-related issues.

Necessarily, increasing mechanization of logging and timber transport leads to a major change in this sector and thereby, an associated high efficiency. One option is to apply fully mechanized technology such as harvesters and forwarders [2]. When applied, the machines can be used not only to produce timber but also for the processing and transport of biomass for energy [3].

If logging residues are to be used for energy production, then logging methods should be adapted accordingly. If the harvesting operation is not adjusted to the subsequent processing of harvesting residues, the quality of the biomass can be very low, and the process becomes economically unviable. Conventional logging residues do not dry uniformly because logging machines usually run over them and therefore, logging residues are in greater contact with soil, absorb soil moisture and are contaminated by the soil and stones. Contamination increases wear of chipper knives during comminution, reduces fuel efficiency, causes problems during combustion and increases the percentage of ash [4]. Hence, the traded quantity of biomass products is less than that available in the forests.

Therefore, it is important to work with data on forest biomass at a regional level [5]. Several studies on this topic have been published with almost the same results i.e., a high amount of biomass is left in the stand, which is positive from a nutrient point of view [6–9], but resources are underutilized from an economic point of view.

However, devoting a part of the harvester's time to logging residue preparation will affect the productivity related to the primary product, as in this case, timber assortments. This was the incentive to carry out a time study describing the effect of integrated harvesting on time consumption. It was thus necessary to conduct a comparative study of conventional and integrated logging operations under as uniform conditions as possible.

2. Materials and Methods

2.1. Study Area

The study was carried out in parts of the Drahanská Highlands in the Czech Republic. The first site was located near Pozořice—stand A (GPS: 49.2193728N, 16.8274086E), where the harvester Rottne H11c (manufacturer Rottne, Rottne, Sweden) operated together with forwarder John Deere 1110D (manufacturer Deere & Company, Moline, IL, USA). The second part of the measurements took place in Kuničky—stand B (GPS: 49.4637433N, 16.6883100E), where a John Deere 1270 harvester was accompanied by a John Deere 1110E forwarder.

The representative stands were chosen according to CTL under typical conditions used in the Czech Republic. Areas with slopes up to 5°, with 95% to 100% dominated by Norway spruce (*Picea abies* (L.) Karst.), aged around 90 years, with an average tree volume of 1.3 m^3 and an average stock volume of 380 m^3 per hectare were chosen. In all cases, clear-felling was used, and no seed trees remained. The contractor operating the machinery ensured that a fixed crew operated at the selected locations. This enabled us, during the data collection, to focus on the studied factors and not to deal with the effects of the operator. The average extraction distance (the distance between the stump and roadside) was 700 m at the first site and 1000 m at the second site.

2.2. Time Study

According to nomenclature [10], this case is a comparative study comparing two variants trying as much as practically possible to control other factors. As reported by [11], the aim of a comparative study is to evaluate the influence of the examined factor on productivity when other factors are almost fixed, such as the influence of workers' experience. The method of this study was subject to the requirements of the client, who was interested in information leading, after further processing, to an increase in productivity and improvement of the economics of the studied logging technology. This is in accordance with the findings of [12] on the focus of time studies. However, in intensive time studies, it is necessary to take into account the skills and experience of the observer [13]. This study was designed and carried out according to the procedure reported by Magagnotti and Spinelli, 2012 [10].

2.3. Hypothesis and Experimental Design

The study was conducted with two harvesters and two forwarders. Harvesters Rottne H11c and John Deere 1270 were operated by operators (a) and (c), respectively. Forwarders John Deere 1110D and

John Deere 1110E were operated by operators (b) and (d), respectively. We did not assess the individual performances of each operator through the evaluation of individual productivity [14]. We did not standardized individual performances between harvester operators (a) and (c) and forwarder operators (b) and (d) because normalizations or corrections may introduce new errors and uncontrollable variability into the measurement data files, and the operation of purposely built variant machines is significantly different [15]. Nevertheless, the experience of the operators was considered representative for the conditions of the study areas. Their skills and experience were declared very similar and for all involved, it was longer than three years. This should ensure sufficient validity of the results of the comparative study. The influence of operator experience may have a significant impact on the performance of the machine. Nonetheless, it was shown that it has a greater influence in early intervention (treatments) in younger stands but slightly less so in the extraction of larger trees, as is the case in this study [16]. Note: From the results, the proportion of time spent harvesting was equal. The same result was found for the forwarding operation.

The monitored harvesters were parametrically entirely comparable. The machines were similar in concept (6 $\times$ 6, all-wheel drive machines with rotating cab, positioning of the crane in the front half-frame in front of the cabin), engine output power (JD 170 kW at 1900 RPM, Rottne 164 kW at 1800 RPM) and the reach of the hydraulic crane (JD 10 m and for Rottne 10.3 m).

Both monitored forwarders—John Deere 1110D and 1110E—differed only in engine output power (120 kW at 2000 RPM versus 136 kW at 1900 RPM) and a rotating cabin. According to the information of the operator of the machinery, the more modern machine 1110E has in the long run, lower fuel consumption (which can be attributed, among other things, to the difference in overall condition and age of the machine) and it has a better performance under difficult conditions. The used tyres differed only in the tyre pattern height. The type and size were identical, just like the hydraulic crane, as well as the size and spacing of stanchions.

In accordance with the assignment and the expected utilization of the study results, we have set the hypothesis and aim as follows: "Time consumption of the integrated logging operation is not significantly different from the time consumption of the commonly used CTL logging operation. Therefore, the application of integrated method is more effective, which will be confirmed/rejected using the time study method to determine the difference in time consumption per unit of production i.e., cubic meter of solid volume measured over bark (o.b.). The logging residues as a side product of timber harvesting are not set as a unit of production, only time spent in logging residue extraction is taken into consideration".

Due to the combinations of two stands and two types of operation, we carried out the measurements based on four variants. However, the other factors have to be confirmed to not influence the results, i.e., operator and machine make and model; therefore, eight combinations had to be studied (see Table 1). In practice, it is not possible to achieve the numerically exact value of measurement conditions. To achieve desired results with an acceptable level of confidence, it was necessary to determine the sample size that is the number of measured cycles.

Table 1. Experimental design of the study.

	Stand A	**Stand B**
Integrated	Rottne H11c + John Deere 1110D Operator (a) + (c)	John Deere 1270 + John Deere 1110E Operator (b) + (d)
Conventional	Rottne H11c + John Deere 1110D Operator (a) + (c)	John Deere 1270 + John Deere 1110E Operator (b) + (d)

2.4. Statistical Analyses and Study Plan

The sample size (number of cycles) required for a reliable mean value was calculated using a statistical formula. We took the variance and the median of a particular population parameter (s2) from previous similar studies with an accent on the knowledge of the contractor. Subsequently, the sample size required for a reliable estimate of the mean diameter may be calculated according to the following formula [17,18]:

$$n = \frac{t^2 \times \left[\frac{Sx \times 100}{\overline{X}}\right]^2}{E^2} \quad (1)$$

where: n—sample size, t—value of normal distribution (example: t = 1.96 for the used 95 % confidence interval), Sx—standard deviation (%), E—Error tolerance for the 10 % confidence interval (%), $\overline{X}$—Average value of time consumed from the preliminary estimate.

According to Equation (1), the minimum number of required repetitions was calculated, i.e., 10. However, the harvesting operation was measured for 180 of the repetitions, and the forwarding operation was measured for 24 repetitions for all methods and locations.

A continuation of the work would usually be the creation of a regression model, as other authors have done. The list of authors who have used linear models include Hånell et al., 2000, Sirén and Aaltio, 2003, and Nakagawa et al., 2007 [19–21]. Authors who designed a quadratic models included Wang and Haarlaa, 2002, Kärhä et al., 2004, and Nurminen et al., 2006 [16,22,23]. However, this study was carried out as a case study ordered by the contractor and limited by the budget. The budget limitation usually plays against the quality and accuracy of the study and the following steps based on Mousavi 2012, Nurminen et al., 2006, Acuna and Kellogg 2008 were not conducted, i.e., testing of the individual measurement samples separately by a t-test and final acceptance or rejection of the null hypothesis. In case, the null hypothesis is not true if the differences in time consumption arises as a result of random effects [23–25]. Due to the lack of the statistical analysis of the data, the results can be presented only in descriptive form.

In assessing the performance of the skidding technology, Wang et al., 2004 concluded that the size of the load and transport distance affects productivity the most. This work focused on the differences arising due to the logging residue processing [26]. Nevertheless, we can still use the time studies as an instrument for defining the influence of various factors on technology productivity.

The operation was recorded in sections using a digital video camera (Sony HDR-CX11E) with a resolution of 10.2 megapixels. The detailed time study was conducted in the office by reviewing field operations recorded by the camcorder. We played the records on a VLC player, and the software TimeStudy was used for recording vehicle cycle times [27]. Operation of the machine was divided into work elements that were considered typical of the harvesting process of each machine (see above). Thus, we monitored only periodically recurring operations during operation, which matched the scope and goals of the project. The operation was measured in Productive Machine Hours (PMH—production time without any delays in operation). For example, relocation (moving between working sites) would still last the same length of time regardless of whether the logging residues were being prepared or not. We exported the recorded time measurement data into MS Excel editor 2013 for processing.

2.5. Productivity Calculation

In the logging operation within this study, the average performance of a harvester and forwarder was measured without any delays. The total volume of the timber extracted was obtained from the on-board computer. The same volume was used as the forwarding volume. The volume was measured in cubic meters of solid volume of the timber measured over bark. The total volume of logging residues was calculated as the sum of turns multiplied by the capacity of the loading area of the forwarder. The volume was measured in cubic meters of bulk volume. The number of productive machine hours spent in different operations was recorded by the operator.

2.6. Division of Working Elements

We used the following elements of the operation for the harvester in this study:

- ***Felling***—machine stops, the hydraulic boom moves, the tree being felled is gripped, cut, directed, and if it is suspended by other trees, then released and pulled down. Before it hits the ground, the trunk may be released to reduce wear of the hydraulic boom and is gripped again.
- ***Delimbing and bucking***—a tree is held by a hydraulic crane horizontally. It is delimbed by knives, and movement of the stem is controlled by feeding rollers of the head. At the same time, a boom moves it toward the temporary storage of logs. Here, individual logs are piled. In the case of logging residues for extraction preparation, delimbing is preferably sited in one location for easier future manipulation.
- ***Preparation of logging residues***—the whole machine rolls back, picks up brushwood, tops of the trees and possibly other parts of the stem, such as around breaks or forks and piles those on for later extraction from a suitable place.
- ***Moving to the next position*** (repositioning)—the machine moves to a place where it will stand during the felling of the next tree.

We used the following elements of the forwarder:

- ***Piled slash/timber loading***—is a set of cyclically repeated movements and grips of the hydraulic crane/grapple, leading to the uploading the forwarder either by logs or logging residues after harvester preparation.
- ***Free slash loading***—is a set of cyclically repeated movements and grips of the hydraulic crane/grapple, consisting of randomly placed slash concentration (piling) in the harvesting area following by uploading the forwarder with logging residues. This slash was not prepared by the harvester.
- ***Driving loaded***—driving of the loaded machine from the stand to the road side, defined by turning the operator's cab seat from the work to transport position.
- ***Unloading***—is a set of cyclically repeated movements and grips of the hydraulic crane/grapple, leading to unloading of the forwarder, including maneuvering during stacking and/or trimming the pile.
- ***Driving empty***—the empty machine drives back to the stand.

3. Results and Discussion

In total, more than 40 h of operations were recorded and evaluated. Tables 2–4 contain the measured results for the studied options, broken down by system, machine model and operator.

The results clearly revealed the following trends for the harvesters:

- The Rottne harvester was newer than the JD 1270 harvester and had a lower failure rate. We could not demonstrate the influence of a modern operator's working environment and software interface on the machine's performance, which is due to latest improvements done by the manufacturer in updated models of similar equipment.
- The experimental design ensured that the difference in the time required for felling and delimbing by different machines was not significant, as well as the influence of the operators.
- Preparation of logging residues did not influence the time required for felling and moving the machines to a new position.
- In addition to time consumption for the direct preparation of brushwood (branches and tops), we detected an increase in time in the delimbing and bucking operation. The operator had to manage not only the location of the logs but also the brushwood. This hampered the work element by an average of 23.5% compared with delimbing and bucking in the case of a conventional harvesting operation.
- Overall, the preparation of harvesting residues increased the time consumption per cycle by 33%, which is equal to 67 s per cycle.

Table 2. Time consumption in the harvesting operation.

Stand	Machine Make and Model	Option	Felling			Delimbing and Bucking			Logging Residues Preparation			Moving to the Next Tree			Total Time Per Cycle
			μ	Min	Max	μ	Min	Max	μ	Min	Max	μ	Min	Max	μ
A	JD 1270	integrated	50.6	22	144	92.8	71	103	41.2	12	54	14.6	8	30	199.2
A	JD 1270	integrated	52	26	70	95.2	72	111	42.4	16	50	13.8	8	24	203.4
B	Rottne H11c	integrated	46	22	66	101.6	76	108	49.4	24	70	10.4	4	22	207.4
B	Rottne H11c	integrated	49.8	12	84	90.4	59	116	39.8	10	72	11.8	6	24	191.8
A	JD 1270	conventional	51.6	20	76	69	50	98				13.8	6	26	134.4
A	JD 1270	conventional	49.8	22	70	70.4	52	94				14.4	10	30	134.6
B	Rottne H11c	conventional	45.4	30	62	75.2	50	102				12	6	26	132.6
B	Rottne H11c	conventional	47	18	68	73.8	46	98				11	4	20	131.8

μ—mean value.

Table 3. Time consumption associated with forwarding operation.

Stand	Machine Make and Model	Option	Loading			Unloading			Driving Loaded			Driving Empty			Total Time Per Cycle
			μ	Min	Max	μ	Min	Max	μ	Min	Max	μ	Min	Max	μ
A	JD 1110E	Integrated	521	498	543	265	230	277	852	841	873	685	652	706	2323
A	JD 1110E	Integrated	536	502	564	243	222	262	846	839	862	697	669	712	2322
B	JD 1110D	Integrated	499	471	516	183	162	195	1147	1121	1189	917	901	930	2746
B	JD 1110D	Integrated	528	460	554	196	167	203	1138	1120	1184	923	897	937	2785
A	JD 1110E	conventional	1135	993	1217	272	237	281	863	851	880	674	661	693	2912
A	JD 1110E	conventional	1098	830	1252	247	229	268	839	822	857	682	671	708	2902
B	JD 1110D	conventional	897	760	1003	179	153	211	1097	1032	1147	915	899	925	3062
B	JD 1110D	conventional	1011	864	1082	188	162	201	1152	1127	1179	931	912	945	3237

μ—mean value.

Table 4. Time consumption in the timber forwarding operation.

Stand	Machine Make and Model	Option	Loading			Unloading			Driving loaded			Driving Empty			Total Time Per Cycle
			μ	Min	Max	μ	Min	Max	μ	Min	Max	μ	Min	Max	μ
A	JD 1110E	integrated	775	713	821	717	653	736	740	727	755	691	658	720	2923
A	JD 1110E	conventional	712	692	747	781	702	816	762	733	803	688	663	713	2943
B	JD 1110D	integrated	745	723	798	761	729	824	983	956	1013	908	889	921	3397
B	JD 1110D	conventional	763	508	783	770	711	803	972	954	998	912	901	925	3417

μ—mean value.

The results clearly revealed the following trends for forwarders:

- The effect of the operator was again negligible.
- The difference between the cycle times of both machines is negligible and statistically insignificant.
- We can assume that in long-term measurements, the difference in performance of operators would be zero, which corresponds to the records of their employer.

The loading and unloading of logging residues compared to timber extraction take less time (71%), although the load occupies a greater load-carrying space volume. The difference in the time of unloading brushwood for various forwarders (mean value μ 255 and 190 s) was caused by the fact that the first brushwood piled onto the tall pile when harvesting residues fell down several times and had to be adjusted. The second just established the pile on the roadside; therefore, the pile did not need to be adjusted. After the experience gained during the measurement, the time needed for unloading brushwood onto a pile up to the height of the cabin was around the average values actually measured, that is, around 220 s.

The bulky volume of harvesting residues affects the time consumption in the driving loaded element. The time spent extracting logging residues was about 15% longer than the time needed for the transport of logs. Bulky material and not providing an easy survey load transported by a forwarder forces the operator to be more careful and reduce the driving speed. We have recorded this fact in all four cases. The average speed of driving loaded with respect to the harvesting residues was about 3.9 km/h, while driving loaded with respect to logs was 4.3 km/h (calculated from the results and average extraction distance).

The driving time back to the stand was always the same regardless of the formal nature of cargo (roundwood or logging residues), which is logical. The empty forwarder drove 5.7 km/h in our study. No effect of formally lost logging residues lying on the striproad or the positioning of the forwarder during the loading and/or unloading stage was registered.

The forwarders were transporting on average about 8.5 m^3 of timber as 4-m long logs. We estimated the volume of the transported logging residues by the size of the loading area to be about 20 m^3 bulk volume. To extract all of the material from the stand, one journey with harvesting residues and three journeys with logs were necessary.

In the case where the forwarder was collecting freely spaced harvesting residues, the time necessary for uploading was on average about 8 min (484 s) longer than that taken by the harvester for the pre-piled option. However, the freely spaced material following the CTL method is better concentrated compared to the motor-manual method (harvested and delimbed by power chain saw).

Productivity and time consumption are the first steps necessary for setting up the strategy of the contractor and are some of the most important information necessary for cost analysis and further decision making. With the increasing number of new machinery (technological development), such studies arise in frequency too. This can be demonstrated by studies by Kulak et al., 2017 or Williams and Ackerman, 2016 [28,29].

In the logging operation within this study, the average performance of the harvester without any delays was calculated to be 35 m^3 s.v./PMH (cubic meters of solid stem volume measured over bark per productive machine hour) of timber or 23.5 35 m^3 s.v./PMH of timber plus 16.45 m^3 b.v./PMH (cubic meters of bulk volume per productive machine hour) of piled logging residues in the integrated operation.

Comparing machine performance leads to taking a lot of factors into the consideration. Generally, the productivity of the harvester per productive machine hour varies between 13 and 42 m^3 s.v./PMH [16,30–32]. The main factors affecting productivity are average tree volume [16,33], number of harvested trees [34], terrain conditions and soil bearing capacity [23], and/or operator skill [35]. Based on the literature review, the results of this study with respect to productivity are comparable.

Describing the real-life deployment of machines, the utilization of the machines needs to be measured. After all, it was work under almost ideal conditions, with a high stem volume of harvested trees, a minimum slope of the terrain, as well as dry and firm ground. The real machine performance according to their operators is considerably lower. In addition, in calculating the performance, we have not taken into account the impact of downtime, repairs, necessary breaks, and so on. For example, Mizaras et al., 2009 noted in their study the breakdown of the working time as follows: 73.7% spent on working operations, such as felling, delimbing, and cross-cutting. In addition, it took another 6.7% of the time to position the whole machine and 19.6% was reported as the time needed for other operations [36]. According to this breakdown, the calculated performance would have to be decreased by almost 20%.

The performance of the forwarder was about 16.32 m^3 s.v./PMH in timber extraction. This matches with the data presented by [37], who declared (under Czech Republic conditions) that the forwarder performance ranges between 7.7 m^3 s.v./PMH and 16.7 m^3 s.v./PMH depending on the average log volume and extraction distance. In the case of logging residue extraction pre-piled by the harvester, the average productivity was 27.5 m^3 b.v./PMH; in the case of freely spaced logging residues, the average forwarder productivity was 23.1 m^3 b.v./PMH. Many authors reported similar results measured in case studies carried out under similar conditions, i.e., 6.0–23.4 m^3 b.v./PMH [38–40].

The main objective, a comparison of the common CTL method with the integrated harvesting method, is based on the operation time of both the harvester and forwarder in the stands described above. In the first option, i.e., the conventional CTL method, the total operation time necessary for timber harvesting without logging residue preparation by the harvester and extraction was 45.6 h (harvesting without piling 10.8 h, timber extraction by the forwarder 23.3 h, harvesting residue extraction by the forwarder 11.5 h). In the second option, i.e., timber harvesting including pre-piling of harvesting residues by the harvester plus extraction of both timber and harvesting residues, the necessary total operation time was 49.4 h (harvesting including pre-piling 16.2 h, timber extraction 23.3 h, harvesting residues extraction 9.7 h).

According to the result, we modeled costs based on the cost calculation method developed within Cost Action FP 0902 [41]. In the case of timber harvesting, the annual cost was 5,395,438 CZK/year and the operational cost was 4681 CZK/PMH. In timber or harvesting residue extraction, the annual cost of the forwarder is calculated as 3,916,909 CZK/year, and the operational cost was 3237 CZK/PMH. Finally, the total cost of the case mentioned above under conventional CTL operation would be about 163,000 CZK; using the integrated method, the total cost would be about 183,000 CZK. The ratio in the period of investigation was 27 CZK = 1 EUR.

4. Conclusions

According to this case study, the integrated harvesting method is less effective in comparison to the conventional CTL method followed by logging residue extraction. The authors can only speculate that only in the case of harmonizing the operation time of both the harvester and forwarder is this strategy valuable. The ratio between the time spent by the harvester and forwarder is 1:3 for the conventional method and 1:2 for the integrated method. This could be used for better balancing the number of machines used to reduce the transport costs. The individual transport of the vehicles may increase overhead costs for management and may increase non-operational support time necessary for servicing. Better performance of the forwarder may be increased by using a grapple purposely designed for logging residue manipulation or at least a versatile grapple useable for both round wood and logging residue manipulation. However, this was not confirmed by this study.

Acknowledgments: The paper was prepared within the framework of research projects of the Internal Grant at Mendel University IGA PSV_2016008. The authors also wish to express their thanks to Kloboucká lesní s.r.o. (contractor) and Vojenské lesy a statky ČR, s.p. (State Military Forest) for providing the possibility for data collection. However, the contractor as the study investor set the limitation of the data presented.

Author Contributions: Martin Pajkoš and Radomír Klvač conceived and designed the experiments; Martin Pajkoš performed the experiments; Martin Pajkoš and Radomír Klvač analyzed the data; Jindřich Neruda contributed reagents/materials/analysis tools; Radomír Klvač and Pawan Kumar Mishra wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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