Investigation of Log Length Accuracy and Harvester Efficiency in Processing of Oak Trees

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Abstract

Harvester use in broadleaves has recently become more effective economically. However, difficulties with delimbing have shown that not all harvesting heads are suitable and efficient for broadleaved species. The typical obstacles are mainly large tree sizes, bends and forks in the trunks and large branches. For these reasons, it is difficult to obtain specific log lengths according to the settings in the harvester on-board computer. The objective of the research was to determine: 1) the accuracy of the log lengths from the bottom, middle and top parts of oak trees, and 2) harvester efficiency in the utilisation of the trunk for logs. The research was carried out on 61-year-old oaks from which logs with an expected length of 250 cm were processed. To achieve this length, a margin of error was set in the harvester computer with minimum and maximum lengths of 252 and 257 cm. For thinning operations, a Ponsse Ergo harvester with a H7 harvesting head was used. After harvesting, manual log measurements were carried out on 280 logs: 69, 142 and 69, from bottom, middle and top parts of the trees, respectively. The largest share of assortments satisfying the minimum requirement of 250–257 cm was obtained from the middle part of the trees (93%), followed by bottom logs (91%) and top logs (88%). The highest frequency of logs, which were too short, were found to be the top logs (9%), while bottom logs were most often too long (6%); therefore, different length settings should be applied to limit such inaccuracies. Analysis of the last log from the highest part of the tree indicated a strong goodness of fit between the top diameter and the DBH; the mean value of the top diameter was 13.3 cm over bark.

*Keywords: oak (*Quercus robur *L.), calibration, cut-to-length, trunk use for logs*

1. Introduction

Since the 1990s, the increasing amount of harvested wood has been one of the factors influencing the expansion of mechanized harvesting in Poland. In 2017, the harvesting of merchantable timber in the State Forests National Forest Holding (SF NFH) aimed to achieve 40.5 million m^3, a considerable increase compared to the 15.9 million m^3 harvested in 1990 (Forestry 2006). The increase in forest growth leads to higher timber production and forest utilisation, changing unfavourable proportions of stands in all age classes (Borecki et al. 2016). Such conditions have been recognised as attractive by forest contractors, who popularised cut-to-length (CTL) technology, and in 2016, approximately 530 harvesters were in operation in Poland (Mederski et al. 2016b). The harvesters were able to cut and process about 30% of the available timber with highly effective thinning operations in pine stands (Mederski et al. 2016a). Among all forest species, Scots pine (*Pinus sylvestris* L.) is the most common in Poland, covering 60% of the land area, while among broadleaves, oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.) claims the biggest share in growing stock, amounting to 8.1% and 6.8% of area and volume, respectively (The National Forest Inventory 2015).

When discussing mechanised harvesting, tree species cannot be ignored. The original harvesters were built to cut and process coniferous trees, mainly spruce in lowland areas. With time, the scope of operations of these machines was broadened to include steep terrains (Stampfer 1999, Frutig et al. 2007) as well as broadleaved stands (Martin et al. 1996 as cited by Sinneau and Cuchet 2001, Spinelli et al. 2002, Spinelli et al. 2009, Mederski 2013). The use of harvesters for broadleaved species makes the machine more universal in Central Europe or Baltic countries, where mixed forests are common, or where a larger share of broadleaves has been introduced (Mederski et al. 2009). In Central Europe, harvester relocation from one plot to another, exclusively among coniferous forest, very often lengthens trips, leading to increased costs. Mixed and broadleaved stands available to the harvester fill these gaps in machine relocation and contribute to better machine utilisation and, due to better logistics, lower fuel consumption and CO_2 emissions. However, the mechanised harvesting of broadleaved trees has resulted in problems associated with delimbing (Labelle et al. 2016), taller stumps in coppice stands (Spinelli et al. 2017), but also larger shavings of the bark and the lateral surface of the processed assortments (Karaszewski et al. 2016). Furthermore, it seems that particular broadleaved species are more favourable for harvesters. In Estonia and Latvia, birch and alder cover approx. 40% of the stands; in Estonia, 95% of the timber is cut by harvesters in final fellings (80% in thinnings), while in Latvia, 70% of the wood is harvested with CTL technology (Moskalik et al. 2017). Not only has the wider use of harvesters been observed in recent years (Mederski et al. 2016b), but there has also been a higher annual use of CTL in European countries (Spinelli et al. 2011, Malinen et al. 2016). It is presumed that the current wider use and higher effectiveness of harvesters are, among other things, due to education, training, automation and organisational knowledge exchange (Häggström and Lindroos 2016).

When discussing the high effectiveness of harvesters, obtaining logs of accurate length has its economic importance. First of all, accurate processing leads to optimal trunk use for logs. However, economic losses can be observed when there are significant inaccuracies, not only due to inefficient use of the trunk: logs which are too long but are destined for the paper industry have to be shortened before debarking, which creates extra costs. In contrast, logs which are too short can be useless for the pallet industry, where an accurate, minimum length is necessary to produce a pallet, and meet safety and certification requirements. Basically, logs which are too short generate extra costs by being transported to the factory and then not being used for their intended purpose.

Bearing in mind the above considerations, the research presented in this paper was carried out to determine to what extent oak branching influences the effectiveness of using a harvester for thinning operations. In particular, the research was designed to mainly find out the influence of oak branching on the accuracy of the cross-cutting of top logs, but also to determine length accuracy in general, in different sections of the tree trunk. In other research, it was revealed that when harvesting aspen, the lengths of top logs (from tree crown where branches were removed) did not differ statistically from those of bottom logs (Mederski et al. 2008). This has been explained by the low density of aspen tree wood, which does not provide much resistance during delimbing, and consequently does not have a negative influence on the workings of the measuring device inside the harvesting head (allowing the trunk to remain in constant contact with the measuring wheel).

In light of these results, a hypothesis was formulated that the branching in oak (hardwood species) may lead to a decrease in the length accuracy of CTL timber assortments and could limit the processing of logs from the top parts of oak trees. Large branch diameter with a high wood density may present resistance to the delimbing knives, which could result in multiple attempts to cut the branches, thus decreasing the accuracy of the length measurement by the measuring wheel. At the same time, large diameter branches may limit log processing in the top parts of the trees. Therefore, the objectives of this research were to find out: 1) the accuracy of log lengths from the bottom, middle and top parts of oak trees, and 2) harvester efficiency in the utilisation of the trunk for logs. Additionally, the study aimed to propose new variants of computer settings to obtain the largest possible share of logs with the expected length.

2. Materials and methods

The research was carried out in compartment 590h (Lidzbark Forest District, northern Poland) during the thinning of a 61-year-old oak (*Quercus robur* L.) dominated stand. Prior to harvesting, the diameter at breast height (DBH) and height (*h*) of 441 trees selected for thinning were measured (Table 1). The DBH and *h* of the remaining trees were also recorded for stand characteristics. The trees selected for the study also had the height of the thickest branch (h_b) measured (Table 1). The DBH was measured once with a calliper (Haglof) with an accuracy of 1 mm, and the results were recorded with an accuracy of 1 cm (a result up to 0.5 cm was rounded down, while 0.6 cm or higher was rounded

Table 1 Characteristics of remaining stand, all harvested trees and those selected for study

Trees	Remaining		Harvested		Harvested & analysed		
Feature	DBH cm	*h* m	DBH cm	*h* m	DBH cm	*h* m	h_b m
Mean	24	18.9	20	17.9	20	18.2	11.9
Minimum	13	11.2	6	8.9	12	11.2	2.2
Maximum	38	27.0	50	24.3	37	22.5	18.3
Standard deviation	5	2.4	6	2.5	6	2.7	2.8
N	137	137	441	441	69	69	69
THI=0.84							

DBH – diameter at breast height
h – tree height
h_b – height of thickest branch on tree
THI – thinning intensity, understood as mean diameter of harvested trees divided by mean diameter of remaining trees

up). The DBH of every tree was measured in a different direction, e.g. if one tree was measured along the N–S axis, the next was measured NE–SW, W–E, etc. Tree height and the thickest branch height were measured using a Vertex Laser (Haglof) with an accuracy of 0.1 m.

Subsequently, the study trees were selected to accurately represent all the DBH classes (to account for the smallest and largest diameters), but a higher frequency of trees was achieved in the more populated DBH classes. For this reason, the trees were selected in such a way that the selected study population (69 trees) presented a normal distribution of DBH. A Shapiro-Francia normality test set at α=0.01 was carried out, the result of which confirmed a normal distribution of DBH for the selected tree population. This was done not only to show the best representation of trees, but also to meet the best criteria for statistical evaluation.

The expected and acceptable assortment lengths for the customer were from 250 to 257 cm. This was applicable for all assortments, from bottom, middle and top tree sections. Therefore, the original harvester computer length settings were 252–257 cm, to meet customer expectations.

The aim was to process logs of a minimum top diameter of 7 cm over bark (minimum diameter of merchantable timber). From the originally selected 69 study trees, 280 processed assortments were measured after cutting: 69 bottom, 142 middle and 69 top logs. More middle logs were cut as two or more assortments were obtained from the middle part of the trees depending on the length of the merchantable trunk.

The length measurements were made using a measuring tape and were accurate to 1 cm. Additionally, the smallest top diameter (one measurement) over the bark of the last assortment (from the highest part of the trunk) from each of the analysed trees was measured with a Digitech Professional electronic calliper with an accuracy of 1 mm. The timber was harvested in the middle of summer, in July, using a Ponsse Ergo single-grip harvester equipped with a H7 harvesting head (Table 2), which according to the manufacturer's information, is suitable for coniferous and broadleaved species. Before thinning, calibration was carried out by an operator according to the current standards and with respect to species. The operator was 29 years old with 5 years' experience working on harvesters, cutting pine and spruce to a large extent, occasionally the broadleaved species - birch and oak.

According to the manufacturer, the H7 harvesting head with three feed rollers (Fig. 1) is designed for harvesting both coniferous and broadleaved trees. Key elements of the machine include: additional feed

Table 2 Technical specifications of H7 harvesting head

Characteristics	Parameters
Measurements and basic parameters	
Weight incl. rotator and hanger	1200 kg
Length	1500 mm
Height with rotator	1680 mm
Width	1540 mm
Power consumption	130–140 kW
Operating pressure	28 MPa
Oil flow requirement	300 l min^{-1}
Saw unit (hydraulic chainsaw)	
Saw bar length	750 mm
Cutting diameter	640 mm
Chain speed	40 m s^{-1}
Chain	0.404"
Feeding unit	
Feeding system	3 rollers
Largest opening	650 mm
Feed power	30 kN
Feed speed	0–5 m s^{-1}
Delimbing unit	
One stationary and four movable knives	
Separately controlled delimbing knives and feed rollers	
Proportional adjustment of rollers and knives	

Fig. 1 Ponsse H7 harvester head (photo by Piotr S. Mederski) and measuring wheel (indicated with an arrow) in central part of head measure length of tree trunk by contact with its surface

rollers on the frame of the harvester head, upper and lower independently controlled hydraulic delimbing knives, as well as the controlled acceleration of the feed rollers. The length accuracy of the harvester measuring system was 1 cm.

The results obtained from the measured harvested assortments were analysed statistically. The data in the three analysed groups (bottom, middle and top parts) were of a different quantity and had no normal distribution. As a result of this, the non-parametric Kruskal-Wallis test was carried out, followed by a Dunn test for the multiple comparison of the means from each group. The analysis was carried out at a significance level of α=0.05 with STATISTICA 10.0. To graph the results, the program package *R* (3.0.2) was used (R Development Core Team, 2013).

3. Results

3.1 Log length

The average assortment length was 252.5 cm, while the minimum and maximum lengths equalled 243 and 266 cm, respectively (Table 3). On average, the longest assortments produced were the bottom logs at 254.1 cm; however, these were characterised by the smallest standard deviation (SD). The top logs had the biggest differentiation with the highest standard deviation (Table 3). The average assortment length of the middle logs (251.9 cm) did not fit the length intervals set in the harvester computer (252–257 cm), although it was within the range of expected length (250–257 cm).

Statistical analysis pointed towards a difference in the length of the top logs and middle logs in comparison to the bottom logs. At the same time, the difference in the top log and middle log lengths was not statistically significant (Table 3).

The largest share of assortments satisfying the minimum requirement of 250–257 cm was obtained from the middle part of the trees (93%), followed by the bottom logs (91%) and top logs (88%) (Fig. 2). At the same time, the bottom logs exhibited parameters

Table 3 Measures of length variability in harvested logs

Parameter	Logs			
	All	Bottom	Middle	Top
Mean, cm	252.5	254.1[b]	251.9[a]	252.3[a]
Minimum, cm	243	249	243	245
Maximum, cm	266	259	266	266
Standard deviation	3.89	1.97	2.41	3.03
N	280	69	142	69

Different letters next to mean values indicate statistically significant differences

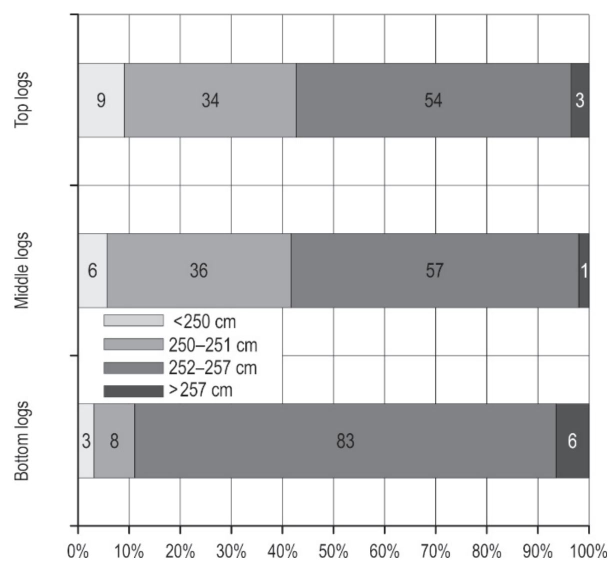

Fig. 2 Proportions of logs from different parts of trees in respective assortment lengths

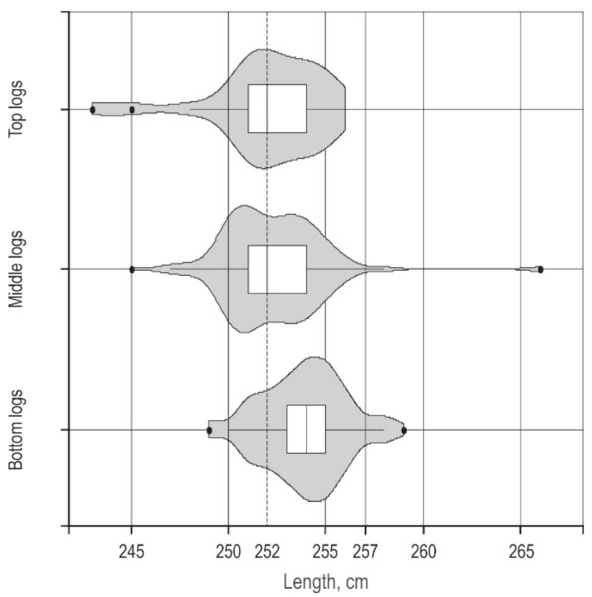

Fig. 3 Vioplot of log length data showing the frequency of data in groups; it presents a symmetrical reflection of kernel density estimation; the centre of each violin contains a boxplot

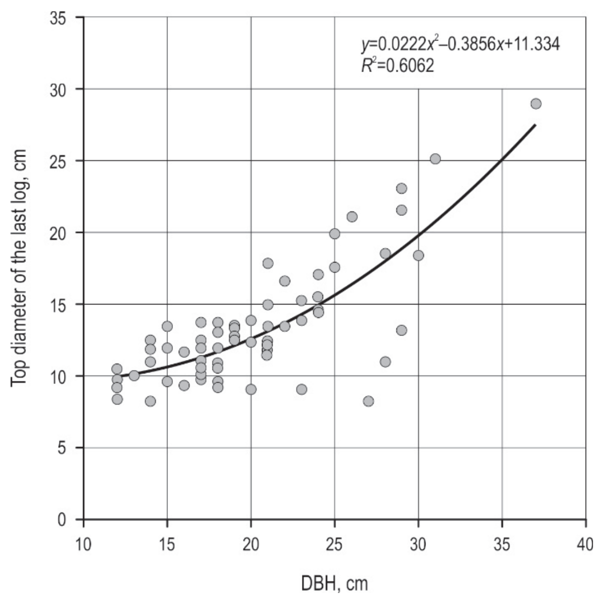

Fig. 4 Relation of top diameter over bark of last log (from highest tree part) to DBH (data from 69 trees: mean=13.3 cm; min.=8.2 cm; max.=29.0 cm; SD=4.1; N=69)

most closely complying with those set on the harvester computer: 83%, with only 57% and 54% for the middle and top logs, respectively (Fig. 2). The top logs also featured the largest number of logs that were too short (9%), while the overly long logs were generally found among the bottom logs (6%).

The most common log length was approximately 254 cm long. In other words, the harvester had a tendency to cut lengths within the middle of the 252–257 cm setting. For assortments from the middle part of the tree, a tendency for logs to be below the assigned value (namely 251 cm) was observed. The top logs tended to exhibit lengths from the middle of the assigned interval as well as constituting the most populous type of overly short assortment (Fig. 3).

3.2 Effectiveness of trunk processing

The oak trees were of a good quality with relatively short crowns representing an average of 35% of the total tree height (Table 1). An analysis of the last log from the highest part of the tree indicated a strong goodness of fit between the top diameter and the DBH (Fig. 4). The mean value of the top diameter was 13.3 cm over bark; however, the largest reached as much as 29.0 cm over bark (Fig. 4). The relation between the DBH and the top diameter expressed by multiple R-squared was relatively high: 0.6062. A particularly dynamic increase in the top diameter of the last log was observed in the trees with a DBH above 25 cm; however, these were not very frequent in the present study (Fig. 4).

4. Discussion

4.1 Log length

The assortments obtained agreed to a large extent with the expected minimum (250 cm) and maximum (257 cm) length. Altogether, 91% of the assortments complied with these lengths. Although the bottom logs were most often (6%) excessively long (Fig. 2), the maximum excess in length was only 2 cm over the assigned values inserted into the harvester on-board computer (Table 3). At the same time, 93% of the assortments, whose length was between 250 and 257 cm, came from the middle part of the trunk.

The observed results point towards the fact that maintaining the maximum length of the thickest (and therefore the heaviest) assortments is the most problematic with respect to the influence of inertia. In the research analysing cut-to-length accuracy by Bembenek et al. (2015), birch and aspen bottom logs were also, on average, the longest. A similar tendency was observed when pine was harvested, where the influence of the assortment length on the accuracy of the cut log was analysed (Różański 1993). In the aforementioned research, the greatest number of assortments (96%) with deviations of ±2 cm was observed with the shortest assortments with an assigned length of 240 cm. Among the longer assortments – 305, 405 and 505 cm – this condition was satisfied by 48%, 35% and 13% of the logs, respectively (Różański 1993). At the same time, the shortest assortments with the smallest diameter and length (240 cm) were obtained from the top parts of pine trees, which can be delimbed very readily (Mederski 2013).

Similar results were obtained by Nieuwenhuis and Dooley (2006), who described the influence of calibration on the precision of cut-to-length Sitka spruce (*Picea sitchensis* (Bong.)). These researchers compared the length measurements obtained using a measuring tape with the harvester measurements for two types of assortment: bottom logs and pulp wood (middle and top logs). In both instances, a smaller value was obtained from the tape measurements. Moreover, this pattern appeared more often in pulp wood, which means it is likely that the measuring wheel lost contact with the pulp log surface more often. At the same time, a reverse tendency was observed for assortment volume, where a smaller value was obtained when measured by the harvester.

It should also be noted that the research of Nieuwenhuis and Dooley (2006) showed that calibration did not always eliminate inaccuracies in measuring assortments, although it did have an influence on the correct determination of volume. Ultimately, however, the fluctuations in volume for pulp wood were unacceptable. Similar conclusions were drawn by Andersson and Dyson (2001), namely that the longer the assortment, the greater the inaccuracy in measuring its length. Moreover, the longest assortments were most frequently found to be too long.

It is important to point out that errors in assortment length measurements may not only be due to machine error. When manual harvesting is conducted using a chainsaw, factors such as branching and curviness have very limited impact (if any) on length accuracy. However, logs that are too short can be more common when bucking with a chainsaw in comparison with a harvester (Zinkevičius et al. 2012).

Bearing in mind the fact that the bucking point is indicated by the measuring device located on the harvesting head, it is interesting to note that in the analysed research the bottom logs were the part of the assortment that most frequently complied with the assigned length. The bottom logs were also the most stable in maintaining lengths as the SD was the lowest, while the top logs were of a greater length variability with the highest SD (Table 3). During the experiment, it was also observed that the bottom ends of the trunks were without visible signs of bark damage. When large wounds are caused by thinning operations (Tavankar et al. 2017), they can also influence the accuracy of harvester measurement.

From the top parts of the trunk, 43% of the assortments were shorter than the assigned length in the computer, however only 9% of the logs were shorter than the expected 250 cm. Overly long logs are obtained when the measuring wheel loses contact with the sides of the trunk measured. An explanation for the overly short logs seems a little more complicated, although two factors stand out from the rest and are worthy of note: surface unevenness (bends, stubs, and loss of bark), around which the measuring wheel rotates, and the lack of contact of the measuring wheel during the reverse movement of the feeding rollers with partially opened movable knives. The results obtained in this research can serve to explain the specific influence of these two factors. The largest percentage of logs with an inadequate length were the top logs. This could be explained by stubs giving the measuring wheel a further distance to travel, hence decreasing the quality of delimbing. At the same time, this assortment most commonly required a retraction of the trunk by the feed rollers. This consequently reduced the impetus of the wood passing through the harvesting head needed to delimb the toughest branches. The repeated processing of the trunk and the multiple delimbing attempts (with the movable knives opening) can lead to the loss of contact of the measuring wheel with the sides of the trunk.

Another significant factor to consider in this research is the importance of the influence of the oak wood density and hardness in relation to increased resistance during delimbing. Mederski et al. (2008) did not observe statistical differences between the lengths of aspen bottom logs and top logs obtained in Lithuania. This was explained by the low density and hardness of that particular tree species and consequently its low resistance during delimbing. At the same time, low frequency rates of trunk retraction through the feed rollers (hence an increase in trunk impetus passing through the harvester) enabled the delimbing of the thickest branches. However, Bembenek et al. (2015) proved that there was a difference (statistically significant) between the length accuracy of thicker bottom logs and thinner top logs of aspen harvested in Poland. The differing results from research carried out on aspen in Lithuania (Mederski et al. 2008) and Poland (Bembenek et al. 2015) suggest that there could also be geographical and/or stand condition factors influencing the morphological features (branch thickness) of the same species, as indicated by Spinelli et al. (2010). The branch size, angle between the branch and trunk, and trunk shape were indicated by Mederski (2013) as factors influencing the quality of delimbing and length accuracy.

These observations support Andersson's (1999) conclusions suggesting that type, quality and assortment size (with no restriction to species) influence the accuracy of bucking to a certain degree. At the same time, Andersson (1999) indicates that neither tree features, nor measurement method or climatic conditions influence bucking accuracy. According to Andersson (1999), the processing of broadleaved trees with a harvester, deep within the vegetation season, contributes to a substantial loss of bark, particularly in birch and alder. This leads to the trunk sliding through the harvester head, consequently resulting in length inaccuracies. Taking into consideration Andersson's (1999) observations, it would be sensible to bear in mind these factors when trying to maintain steady assortment lengths in different environments.

4.2 Effectiveness of trunk processing

A particularly important fact to emerge out of researching the harvesting of oak was the observation of a significant relationship between the top diameter of the assortments from the top part of the trunk and the DBH (Fig. 4). This relationship was present due to natural tree morphology – the thicker the tree, the bigger and longer the crown. Consequently, bigger and longer crowns had thicker branches growing lower on the stem (where there were bigger diameters), and these obstructed delimbing in the top section of the trees. In the case of all the remaining timber with a diameter of over 20 cm, of particular importance is the fact that there are significant levels of timber waste (tree tops). This also points towards certain limitations to harvester use in the processing of oak with larger diameter branches. As can be seen in research by Mederski (2013), the harvesting of pine in Central Europe allowed for the production of pine assortments with average minimum diameters of 9.4 and 10.6 cm over the bark (for 45 and 60-year-old pines, respectively), when the expected diameter was 7 cm over the bark. However, tree tops are in growing demand and can have a high value in the energy sector, especially when the quality of logging residues is satisfactory (Nilsson et al. 2016). As harvesters can have limitations in the processing of logs of smaller diameters from the tree tops, CTL technology in broadleaved stands can naturally contribute to a larger share of a renewable energy source. The relationship between the size of the top diameter of the last log and the DBH can be explained by the fact that trees with the biggest diameter have a stronger build, a longer crown and thicker branches. Thick branches, in particular, interfered and limited delimbing by the harvester head. It should also be assumed that the assortment length from the top logs of the thickest tree is even less accurate due to the lower quality of delimbing of the thickest branches (Mederski 2013).

4.3 Proposed corrections for error window

Bearing in mind the tendencies in the bucking of the trunk into logs (with respect to the three aforementioned trunk sections), it is suggested that for top and middle logs different settings should be applied. In order to attain the optimal distribution, spread within the 250–257 cm limits with the minimum interval values for oak trees (of considered sizes and age), the following settings could be applied to the Ponsse Ergo (with the H7 head) harvester on-board computer: 254–257 cm for top and middle logs (the lower value moved up by 2 cm), and 252–255 cm for bottom logs (the higher value lowered by 2 cm). The proposed settings should result in fewer logs that are too short when obtained from the top and middle parts of the trunk, as well as a lower number of bottom logs that are too long.

5. Conclusions

To summarise, the results obtained for the analysed harvester and species (oak), three dependencies can be clearly observed:

- ⇒ the larger (and heavier) the assortment, the greater the tendency to produce overly long timber, particularly in the case of bottom logs
- ⇒ the tested harvester had a tendency to produce top logs that were too short
- ⇒ the use of the trunk was limited, and the larger the DBH, the more of the top of the tree remained unprocessed

Generally, the bottom logs were, on average, approximately 2 cm longer than the middle and top logs. At the same time, the highest standard deviation of length appeared in the top logs, with the lowest in the bottom logs. The length of the bottom log assortments differed statistically from those of the other trunk assortments.

A Ponsse Ergo harvester equipped with a H7 harvesting head was an appropriate solution for harvesting a hardwood, broadleaved species, in a 61-year-old oak stand. The greatest accuracy of log length was achieved for the bottom logs, while the biggest share of logs that were too short were obtained from the top part of the trees. The mean length values indicated that the bottom logs were cut within the middle range of the limits of error, but the top and middle logs were close to the minimum length limit set in the harvester computer. To obtain better results, it is suggested that different length tolerances should be applied: 254–257 cm for thinner top and middle logs, and 252–255 cm for bottom logs. Some difficulties were observed when processing top logs from thicker trees. The mean top diameter of 13.3 cm over bark of the last log suggests that there is still potential for log processing from these parts of trees. The thicker the tree, the larger the tree top that remains. Wider use of a harvester, for coniferous and broadleaved stands in Central Europe, allows for the better utilisation of CTL technology within a given area by reducing machine relocation costs.

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6. References

Andersson, B., 1999: Log measuring accuracy of cut-to-length harvesters and processors. Forest Engineering Research Institute of Canada, Vancouver, Canada, Final Report of project CC97139-ORE, 18 p.

Bembenek, M., Mederski, P.S., Karaszewski, Z., Łacka, A., Grzywiński, W., Węgiel, A., Giefing, D.F., Erler, J., 2015: Length accuracy of logs from birch and aspen harvested in thinning operations. Turkish Journal of Agriculture and Forestry 39(6): 845–850.

Borecki, T., Stępień, E., Wójcik, R., Orzechowski, M., 2016: Verification of the principles of accounting for the size of the allowable fellings in forest management planning. Drewno 59(197): 61–75.

Cacot, E., Bigot, M., Cuchet, E., 2006: Developing full-mechanized harvesting systems for broadleaved trees: a challenge to face the reduction of the manual workface and to sustain the supply of hardwood industries. In Proc., 29th Council on Forest Engineering (COFE) Conference: Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World July 22 to August 2, eds. W. Chung and H.S. Han, Coeur d'Alene, USA, 9 p.

Forestry, 2006: Central Statistical Office of Poland, Warsaw, 285 p.

Frutig, F., Fahrni, F., Stettler, A., Egger, A., 2007: Mechanisierte Holzernte in Hanglagen (Mechanised timber harvesting on slopes). Wald und Holz 4: 47–52.

Glöde, D., 1999: Single- and double-grip harvesters – productive measurements in final cutting of shelterwood. Journal of Forest Engineering 10(2): 63–74.

Häggström, C., Lindroos, O., 2016: Human, technology, organization and environment – a human factors perspective on performance in forest harvesting. International Journal of Forest Engineering 27(2): 67–78.

Karaszewski, Z., Łacka, A., Mederski, P.S., Noskowiak, A., Bembenek, M., 2016: Damage caused by harvester head feed rollers to alder, pine and spruce. Drewno 59(197): 77–88.

Labelle, E.R., Soucy, M., Cyr, A., Pelletier, G., 2016: Effect of Tree Form on the Productivity of a Cut-to-Length Harvester in a Hardwood Dominated Stand. Croatian Journal of Forest Engineering 37(1): 175–183.

Malinen, J., Laitila, J., Väätäinen, K., Viitamäki, K., 2016: Variation in age, annual usage and resale price of cut-to-length machinery in different regions of Europe. International Journal of Forest Engineering 27(2): 95–102.

Martin, P., Lapeyre, D., Douchet, O., Restoy, G., Guegand, G., 1996: Récolte mécanisée des taillis en bois ronds (Mechanised timber harvesting in coppice stands). AFOCEL Fiche Information-Forêt 4(540): 1–6.

Mederski, P.S., 2013: The potential of harvester use for thinning operations in mixed birch-pine stands. Poznań University of Life Sciences Press, Poznań, 109 p.

Mederski, P.S., Bembenek, M., Jakubowski, M., Zinkevičius, R., 2008: Length accuracy of aspen logs harvested with CTL 40HW harvester head designed for broadleaved species. Human and Nature Safety 14: 241–243.

Mederski, P.S., Bembenek, M., Karaszewski, Z., Łacka, A., Szczepańska-Álvarez, A., Rosińska, M., 2016a: Estimating and Modelling Harvester Productivity in Pine Stands of Different Ages, Densities and Thinning Intensities. Croatian Journal of Forest Engineering 37(1): 27–36.

Mederski, P.S., Jakubowski, M., Karaszewski, Z., 2009: The Polish landscape changing due to forest policy and forest management. iForest 2(4): 140–142.

Mederski, P.S., Karaszewski, Z., Rosińska, M., Bembenek, M., 2016b: Dynamics of harvester fleet change in Poland and factors determining machine occurrence. Sylwan 160(10): 795–804.

Moskalik, T., Borz, S.A., Dvořák, J., Ferencik, M., Glushkov, S., Muiste, P., Lazdiņš, A., Styranivsky, O., 2017: Timber Harvesting Methods in Eastern European Countries: a Review. Croatian Journal of Forest Engineering 38(2): 231–241.

Nillson, D., Pettersson, R., Thörnqvist, T., Nylinder, M., 2016: The importance of accurate measurement of comminuted logging residues' moisture contents for small-scale forest owners. Drewno 59(198): 99–110.

R Development Core Team, 2013: *R:* A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Różański, H., 1993: Wydajność i dokładność wyróbki drewna harwesterem wysięgnikowym Lokomo FMG 990/756 (Productivity and bucking accuracy of the Lokomo FMG 990/756 harvester). Przegląd Techniki Rolniczej i Leśnej 10: 18–19.

Sionneau, J., Cuchet, E. 2001: Mechanisation of thinnings in hardwood, the French experience. In Proc., International

Conference: Thinnings: A valuable forest management tool, IUFRO Unit 3.09.00 and FERIC, Natural Resources Canada and Canadian Forest Service, Québec, Canada 2001, 8 p.

Spinelli, R., Hartsough, B.R., Magagnotti, N., 2010: Productivity standards for harvesters and processors in Italy. Forest Products Journal 60(3): 226–235.

Spinelli, R., Magagnotti, N., Nati, C., 2009: Options for the mechanised processing of hardwood trees in Mediterranean forests. International Journal of Forest Engineering 20(1): 39–44.

Spinelli, R., Magagnotti, N., Picchi, G., 2011: Annual use, economic life and residual value of cut-to-length harvesting machines. Journal of Forest Economics 17(4): 378–387.

Spinelli, R., Magagnotti, N., Schweier, J., 2017: Trends and Perspectives in Coppice Harvesting. Croatian Journal of Forest Engineering 38(2): 219–230.

Spinelli, R., Owende, P.M.O., Ward, S.M., 2002: Productivity and cost of CTL harvesting of Eucaliptus globulus stands using excavator-based harvesters. Forest Products Journal 52(1): 67–77.

Stampfer, K. 1999: Influence of terrain conditions and thinning regimes on productivity of a track-based steep slope harvester. In Proc., International Mountain Logging and 10th Pacific Northwest Skyline Symposium March 28 – April 1, eds. J. Sessions and W. Chung, Corvallis, Oregon, USA, 10 p.

Tavankar, F., Picchio, R., Nikooy, M., Lo Monaco, A., Venanzi, R., Iranparast Bodaghi, A., 2017: Healing rate of logging wounds on broadleaf trees in Hyrcanian forest with some technological implications. Drewno 60(199): 65–80.

The National Forest Inventory, 2015: Bureau for Forest Management and Geodesy, Sękocin Stary, Poland, 176 p.

Zinkevičius, R., Steponavičius, D., Vitunskas, D., Činga, G., 2012: Comparison of harvester and motor-manual logging in intermediate cuttings of deciduous stands. Turkish Journal of Agriculture and Forestry 36(5): 591–600.

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