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Modelling of forwarding distance to maximize the utilization of medium and high-power harvester technology

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Abstract

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Every technologist aims to maximize the performance and capacity of vehicles, particularly when deployed in technological lines. To maximize the utilization of harvester technology, particularly of forwarders following the work of harvesters, it is useful to determine the maximum forwarding distance for consequent transport of timber, which was the aim of this study. The analysis presented in this study was conducted in medium and high-power vehicles which are dominantly deployed in the Czech Republic. The same performance of harvesters and forwarders is achieved by the calculation of the maximum forwarding distance. Other variables are constant for the time models (average load volume of forwarders is 12.1 m^3 and the mean-tree volume is constant for every logged stem). Our conclusions suggested a maximum forwarding distance ranging from 116 to 1,052 m, depending on the decreasing mean-tree volume which ranged from 0.3 to 1.0 m^3 per tree in the monitored logged stand.

Keywords: forwarder; performance standards; work productivity; time consumption; timber transport

The increasing proportion of cut-to-length logging and the associated expensive harvester technology are becoming the focus of targeted research driven by the objective to maximize performance and work efficiency. The number of forwarders in the Czech Republic at the end of 2013 stood at 779 and cut-to-length logging accounted for 31% of the annual volume of harvested timber, which represents 4.7 million m^3 of timber (Ministry of Agriculture of the Czech Republic 2014). Owing to its high investment costs and the highly diverse production conditions throughout Europe, the proportion of cut-to-length logging in individual countries differs, with approximately 25% in Russia (Gerasimov et al. 2013), about 50% in Germany (Opferkuch et al. 2014) and almost 90% in Scandinavian countries, particularly Sweden and Finland (Gellerstedt, Dahlin 1999; Nordfjell et al. 2010). Timber haulage by forwarders, along with cable and horse skidding, is considered a nature-friendly technology and receives government subsidies at the average of 0.76 EUR·m^{-3} (Ministry of Agriculture of the Czech Republic 2014).

Machinery performance is influenced by a number of both changeable and constant factors. Terrain conditions, among them slope inclination, obstacles and ground bearing capacity (Persson 2013) are particularly important and as such are specified in

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terrain classifications (Berg 1992; Simanov et al. 1993) and condition the corresponding technological specifications (recommended mechanization for the given terrain). Acceptable terrains for forwarders encompass conditionally bearable and bearable terrains with allowable bearing pressure on the soil foundations exceeding 150 kPa, obstacle-free terrains with maximum obstacle height of up to 50 cm or with obstacles more than 5 m apart, as well as terrains with slope inclination of up to 33% (Simanov et al. 1993). Deployment of harvesters and forwarders in terrains with the slope inclination exceeding 30% results in impaired performance (Ghaffarian et al. 2007; Zimbalatti, Proto 2010). Long-term changeable factors (logging intensity, concentration of timber intended for logging, form of forest management, technological parameters of the logged trees, etc.), along with factors changeable in the short-term horizon (transport conditions, distribution of roadside landings, produced log lengths, time schedules of individual workplaces) open up a much more significant space for effective planning of any technology deployment (Rónay, Dejmal 1991). Other factors affecting work productivity are represented by technical parameters of the deployed machinery, the most significant being the forwarders' load volume. This volume may range from 3 to 25 m^3, depending on the make and type of vehicle. In performance standards the load volume is often substituted by engine performance or load-bearing capacity, as a certain correlation between these technical parameters is expected (Dvořák et al. 2010). Last but not least, the human factor, in the form of an operator's experience and practice, is also reflected in the corresponding work performance (Szewczyk et al. 2016).

Owing to the above-mentioned numerous factors affecting work performance, basic factors – i.e. mean-tree volume, forwarding distance, engine performance and type of logging – are selected for the purpose of determining the basic standard in the Czech Republic (Dvořák et al. 2011). Other factors are taken into account by percentage adjustment of the basic standard or through supplementary standards.

Most of the immediately changeable factors encompass technical and technological parameters. One of the most significant short-term factors which affect the volume of forwarded timber in time, regardless of the mechanization used, is forwarding distance (Nouzová 1995; Dvořák et al. 2011; Stankić et. al. 2012; Musat et al. 2016). For the purposes of research, forwarding distance is defined as a distance from the centre of the production line, where logging takes place, to a roadside landing and as such can be considered constant for the given workplace. Increasing forwarding distance teamed with lower load volume and insufficient utilization of the vehicle's full load volume result in progressively decreasing performance of a forwarder. Within the operation time, the time necessary for transporting load to the roadside landing and driving the vehicle back to the forest stand comes second after the time necessary for loading timber in the stand.

Every technologist and economist should aim to maximize the utilization of all vehicles within a production line with the objective to maximize work efficiency. In a technological line consisting of a harvester and a forwarder in our case it is difficult to ensure full performance of both vehicles. In our case it is the distance necessary for forwarding timber from a forest stand to a roadside landing which significantly influences machine performance and in most cases represents the key factor in performance standards for planning timber forwarding productivity regardless of the means of transport (Nouzová 1995; Dvořák et al. 2011). Among other things, this fact allows us to select suitable roadside landings at an acceptable (optimum) distance from the production block. It is not therefore necessary to opt for the nearest spot by a paved forest road but it also allows us to choose another suitable spot for a forest depot, which may consequently result in higher efficiency in the forwarding of timber from forest land by haul rigs.

The aim of this analysis is therefore to optimize the work of a harvester technological line in relation to forwarding distances to ensure the maximum utilization of a forwarder with respect to the position of the respective roadside landing. By planning the logistics of timber transport from stump to the final customer we can achieve considerable savings. Timber forwarding from stump to roadside landing plays an important part in these savings.

MATERIAL AND METHODS

Area measurement. Analytical calculations draw on models created based on data from the areas of Central, South and West Bohemia (Fig. 1). The measurements for the analysis were performed at the Forest Districts Horní Blatná and Toužim (Forests of the Czech Republic, State Enterprise), Forest School Enterprise Kostelec nad Černými lesy, Division Hořovice (Military Forests and Farms, State Enterprise) and Forest Enterprises Konopiště and Boubín (Forests of the Czech Republic, State Enterprise).

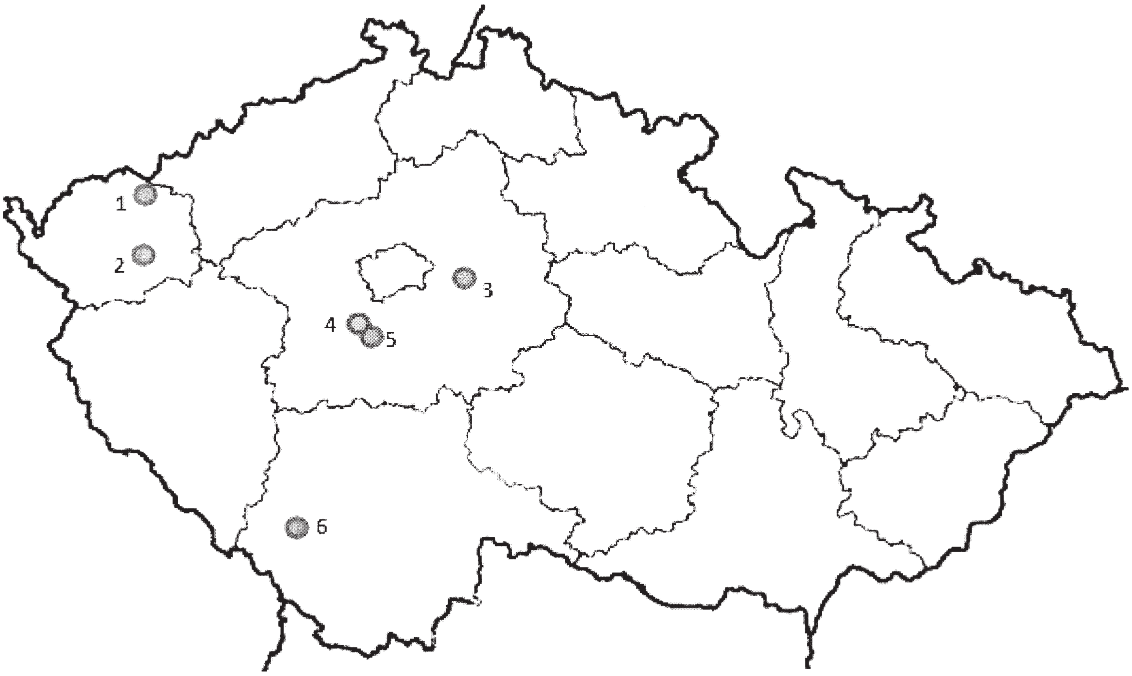

Fig. 1. Regions of conducted measurements

1 – Horní Blatná Forest District (FD), 2 – Toužim FD, 3 – Kostelec nad Černými lesy Forest School Enterprise, 4 – Hořovice Division, 5 – Dobříš Forest Enterprise (FE) (at present Konopiště FE), 6 – Boubín FE

Production conditions. The measurements were done in 11 operators who were expected to reach the planned production targets while fulfilling and observing all work and safety regulations. The optimization of forwarding distance focuses on medium and high-power forwarders. This group encompasses forwarders with engine performance over 60 kW. Time consumption and forwarding distance were measured for the forwarders John Deere and Komatsu (Valmet). 147 forwarder lines were selected for this study, where the time consumption and forwarding distances were measured for a period of three years. The forwarding distance ranged from 10 to 800 m, average forwarding distance was 355 m and the mean distance (median) was 430 m. The measurement time did not have to be contingent to any season and other factors were chosen at random.

Measuring and evaluation methodology. The task is to conduct experimental measurements of time consumption by forwarders in standard conditions of the Czech forest sector. The measurements were done by taking gradual snapshots of forwarder work operations and by snapshots of forwarder operator's work shift determining batch and shift times. The "method of chronometric analysis" was applied in direct experimental measurements and consequent time analyses. Work operations are measured using continuous chronometry by direct observation of the work process and taking snapshots in randomly selected forest stands or production units using the so-called "method of measuring gradual time". The production stage of timber forwarding is divided into four work operations: (*i*) time for the ride of the machine without load from a roadside landing to the skidding site (t'_{A126}), (*ii*) time for creating the load (t'_{A127}), (*iii*) time for the ride of the machine with the load from the skidding site to a roadside landing (t'_{A128}), (*iv*) time for off-loading timber at the roadside landing (t'_{A129}). The measurements are taken in minutes, other shift times are also measured in minutes: preparation and concluding of work – T_{B101}, technical servicing of the work place – T_{B102}, technical maintenance of the vehicle – T_{C104}, minor repairs – T_{C105}, breaks – T_2. Control measurements were done in videos made during harvester operation. The method of unit time consumption measurements, extended to include shift and batch time and load volume measurements, was published by Dvořák et al. (2011).

Similar to standardization of most transport activities, the primary independent factors include the mean-tree volume, forwarding distance and the forwarder load volume (Eriksson, Lindroos 2014). The primarily analysed forwarding distance for this study was recorded from the centre of a forest stand to the roadside landing in forest maps. The mean-tree volume in stands was determined from *.prd files provided by the harvester measuring system. Load volume was calculated in spatial measurements based on the length of forwarded logs, width of forwarder loading area and load height (all measured at the roadside landing with a tape measure). The bulk volume is converted into solid metres using the conversion coefficient 0.6. From these the average load volume was calculated.

Consumption of working time was used to create two time models for the production of a cubic meter of timber by harvester and forwarder. The models have been established on the basis of the correlation analysis. Consumption of working time was analysed depending on the mean-tree volume of the felled spruce for harvesters and depending on the forwarding distances and mean-tree volume of the felled spruce for forwarders. The analytical procedure of determining the maximum recommended forwarding distance is determined by equality of these two models of time consumption necessary for producing a cubic metre of timber by a harvester (in $s \cdot m^{-3}$) and model of time consumption necessary for forwarding the same volume of timber from a stand to a roadside landing by a forwarder.

RESULTS

The average unit time consumption per load was 47 min with standard deviation of 15.07 min per load, upon average load of 12.1 m^3. The normal (standardized) time consumption (cleaned of loss times) is shown in Fig. 2, where the highest proportion of an average shift length of 10.12 h is taken up by operation time at 76%.

The production stage of timber forwarding consisted of four work operations. The highest consumption is taken up by time necessary for creating a load, which may range from 2 to 50 min per load. It is followed by time for unloading at roadside landing, which consumes from 2 to 25 min. The shortest time consumption falls to work operations "driving unloaded vehicle from roadside landing to extraction site" and "driving loaded vehicle from extraction site to roadside landing". Both work operations take up virtually the same time, regardless of the fact whether the forwarder is loaded or unloaded. The time consumption ranges from 1 to 19 min and/or 21 min. Average proportions of time consumption per work operation are shown in Fig. 3.

Performance of medium and high-power harvesters

One of the models expressing the time consumption necessary for felling and processing a tree by a medium and high-power harvester in relation to the mean-tree volume was published by Dvořák et al. (2011). The formula is derived from spruce and pine harvesting in advance and planned principal felling. Its unit times are proportionally increased by coeffi-

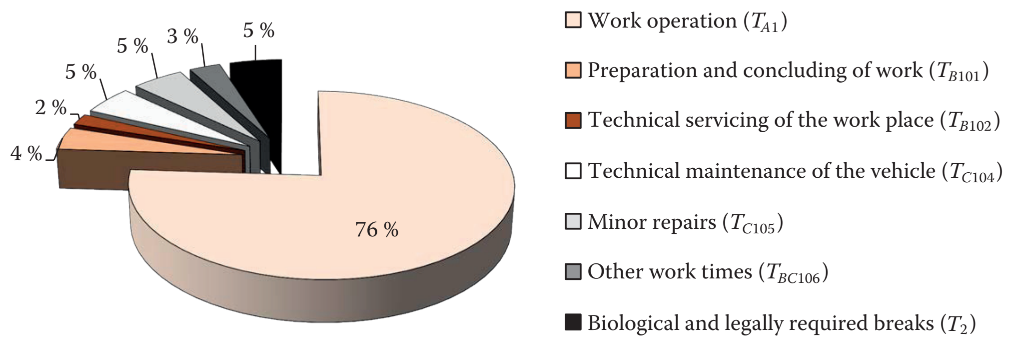

Fig. 2. Review of the normal consumption of a forwarder's shift time

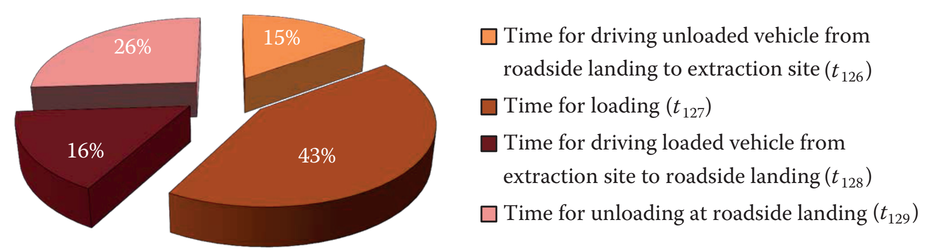

Fig. 3. Average share of work operations at the production stage of timber forwarding

cient k_{BC} = 1.34 to include shift and batch times, and by coefficient k_2 = 1.07 to include the time for legally required breaks (Act No. 262/2006 Coll.). The total time for processing a tree can be quantified by Eq. 1:

$$f(t_{HA}) = t_{SM} = \sum_{i=1}^{5} t_{A12iSM}(h_{SM}) = 174.30907 \times h_{SM}^{0.23125} \quad (1)$$

where:

t_{HA} – time of unit for felling and processing the tree (s per tree),

t_{SM} – total time consumption for felling and processing a tree by a harvester (s per tree),

t_{A12iSM} – time for a work operation within the production stage of felling (s per tree),

h_{SM} – mean-tree volume of the felled tree (m^3 per stem).

The model presented above forms a foundation for the basic performance standard in production conditions of the Czech Republic (Eq. 2):

$$t_{SM-HA} = \frac{f(t_{HA})}{h_{SM}} \quad (2)$$

where:

t_{SM-HA} – total time for processing a solid cubic meter ($s \cdot m^{-3}$).

Performance of medium and high-power forwarders

The performance is derived from a model created for the time consumption necessary for forwarding a single load (Dvořák et al. 2011). The total time consumption is conditioned by the mean-tree volume of the felled stem and the forwarding distance. It is valid both for advance and planned principal felling, for produced logs of 2 to 6 m in length, regardless of the tree species. Experimental measurements determined the average volume capacity of a forwarder at 12.1 m^3. Unit times are proportionally increased by coefficient k_{BC} = 1.25 to include shift and batch times, and by coefficient k_2 = 1.06 to include the time for legally required breaks (Act No. 262/2006 Coll.). The total time for processing a tree can be quantified by Eq. 3:

$$f(t_{VT}) = t_{SM} = \sum_{i=1}^{4} t_{A12iSM}(h_{SM}) = $$
$$= 56.426 - 25.684 \times h_{SM} + 0.038 \times L \quad (3)$$

where:

t_{VT} – time of unit for forwarding a load (min per load),

t_{SM} – total time consumption for forwarding a load (min per load),

t_{A12iSM} – time for a work operation within the production stage of forwarding (min per load),

h_{SM} – mean-tree volume of the felled spruce (m^3 per stem),

L – forwarding distance (m).

The standard for the planned performance of a forwarder is defined by Eq. 4:

$$t_{SM-VT} = \frac{60 \times f(t_{VT})}{V} \quad (4)$$

where:

t_{SM-VT} – total time consumption for forwarding a solid cubic meter ($s \cdot m^{-3}$),

V – load volume of a forwarder (m^3).

Modelling of maximum allowable forwarding distance

The optimum forwarding distance draws on the time consumption model for medium and high-power harvesters and forwarders, which was designed for Forests of the Czech Republic, State Enterprise (Dvořák et al. 2010). Models of harvester and forwarder performance were converted into mathematical models (Dvořák et al. 2013) and performance can be determined on-line using a web application on http://vnhu.forestoffice.eu/.

The maximum utilization of a harvester technological line can be achieved by identical time consumption for the harvester production of a cubic meter of timber and the same time consumption for forwarding the timber to a roadside landing. Such results can be achieved by parity of Eqs 2 and 4 (Eq. 5):

$$\frac{f(t_{HA})}{h_{SM}} = \frac{60 \times f(t_{VT})}{V} \quad (5)$$

$$\frac{174.30907 \times h_{SM}^{0.28125}}{h_{SM}} = \frac{60 \times (56.426 - 25.684 \times h_{SM} + 0.038 \times L)}{V} \quad (6)$$

Eq. 6 clearly shows that three variables remain for the production line:

(*i*) Mean-tree volume which, after marking the extent of felling at the work site, is constant for both harvester and forwarder operators;

(*ii*) Load volume of the forwarder, which may be variable with respect to the technical aspects. Technically it is possible to adjust the load volume in selected vehicles by extending the distance between stakes, raising the stakes or by not loading the vehicle fully. In all these cases the full load capacity of the vehicle is not utilized. Moreover, in a number of cases the maximum utilization of the vehicle may not be achieved due to other technological reasons (e.g. poor soil bearing capacity, highly structured production of assortments);

(*iii*) Forwarding distance, which represents a significant factor in work planning. In case of the maximum utilization of a forwarder, the forwarding distance may be expressed by Eq. 7, following adjustment of Eq. 6:

$$L = 675.89 \times (-2.19 + 1.37 \times h_{SM}^{-0.76875} + h_{SM}) \qquad (7)$$

Forwarding distance thus may range from 116 to 1,052 m in relation to the mean-tree volume of harvested trees, which ranged from 0.3 to 1.0 m^3 per stem in 95% of all analysed stands (Table 1). In extreme cases it could reach 1,800.0 m for the tree volume of 0.2 m^3 per stem.

The results presented above recommend a maximum forwarding distance ranging from 116 to 1,052 m, upon which the performance of a harvester technological line will range from 8.2 to 20.7 $m^3 \cdot h^{-1}$ depending on the tree volume of 0.3–1.0 m^3 per stem. Fig. 4, which shows the maximum recommended forwarding distance in relation to the mean-tree volume, reveals an increase in forwarding distance of up to 907% between the limit values of the monitored volume of harvested trees in a forest stand.

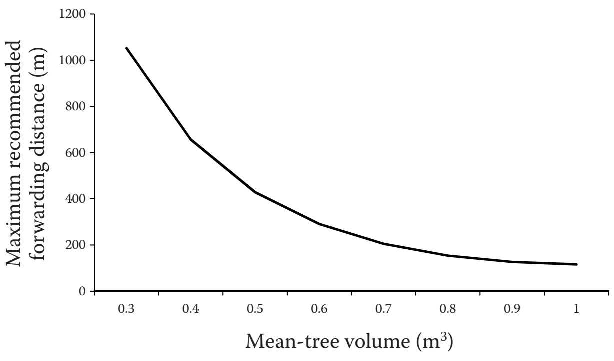

Fig. 4. Maximum recommended forwarding distance in relation to the mean-tree volume

DISCUSSION AND CONCLUSIONS

The study analyses the possibility of adjusting the performance of forwarders and harvesters in relation to forwarding distance. It draws on a study prepared for Forests of the Czech Republic, State Enterprise, which was conducted by the author of the paper (Dvořák et al. 2010).

Forwarding distance represents one of the variable independent factors which conditions the performance standard and performance of forwarders. The aim of every technologist should be to determine the maximum forwarding distance to minimize operation costs, store the produced logs on a suitable roadside landing to safeguard further transport and to maximize the utilization of vehicles within the harvester technological line (harvester vs. forwarder). The time consumption for timber forwarding and driving the vehicle back to the stand accounts for 31% of operation time in the study. This ratio roughly corresponds with results obtained in other studies, which report the time consumption for loading and load preparation at 40–50%, unloading at 20% and timber forwarding and driving back to the stand at approximately 30–40% of the operation time (Ghaffarian et al. 2007; Uusitalo 2010; Eriksson, Lindroos 2014). Time consumption in timber forwarding cannot be seen as an unchanging factor, as the forwarder speed is lower in shorter forwarding distances and vice versa (Nurminen et al. 2006).

The recommended maximum forwarding distance increases with lower mean-tree volume (Nordfjell et al. 2010). Based on the results obtained the recommended forwarding distance should range from 116 to 1,052 m for the mean-tree volumes of 0.3–1.0 m^3, respectively. The study does not analyse the economic costs of timber forwarding. Owing to the fact that costs increase with increasing forwarding distance it is recommended not to exceed the recommended maximum forwarding distance. If it should be exceeded, the harvester idle time can be expected to increase, thus requiring further costs. When applying the maximum recommended forwarding distance, the factors which should be taken into consideration include selection of a suitable roadside landing with respect to further transport of timber to conversion depots or customers and the probability of increased costs due to the harvester idle time as a result of exceeding the recommended maximum

Table 1. Recommended maximum forwarding distance

Stem volume (m^3 per stem)	Maximum forwarding distance (m)	Harvester line performance ($m^3 \cdot h^{-1}$)
0.3	1,052	8.2
0.4	657	10.2
0.5	429	12.1
0.6	291	13.9
0.7	205	15.7
0.8	154	17.4
0.9	127	19.0
1.0	116	20.7

forwarded distance. On the other hand, it should be taken into account that the recommended maximum forwarding distance increases when forwarding timber with lower volume, as it is associated with lower profit and the losses might increase even if the performance of both harvester and forwarder is balanced.

The presented mathematical analysis, with a standard deviation, supports general operational recommendations as well as conclusions drawn by foreign studies. The most often recommended optimum forwarding distance is 600 m, the maximum forwarding distance in more difficult terrains ranges from 800 to 1,200 m (MacDonald 1999; Spinelli et al. 2004; Brink, McEwan 2016; Pulkki 2016).

The model is proposed as technical support for work planning upon parallel work of harvester and forwarder as a single unit. On the other hand, it must be taken into consideration that with forwarding distance increasing from 200 to 400 m the forwarder performance decreases by 10–17%, depending on the type of felling (Nurminen et al. 2006). Ghaffarian et al. (2007) stated in their study that when increasing the forwarding distance by approximately 250 m, the time consumption for timber forwarding may increase by up to 20 min per single work cycle. Our measurements did not reveal such a significant difference, showing approximately a 15-min increase upon increasing the forwarding distance by 250 m (Dvořák et al. 2011). At the same time, the load structure plays a role as well, as the forwarder performance in forwarding 4–5 m saw logs will be 40–43% higher than in forwarding two-metre pulpwood (Nurminen et al. 2006).

Based on the trend observable in the application of cut-to-length method we may expect a further increase in harvester technology deployment both in the Czech Republic and in other European countries. Forwarders find a broad application not only in the forwarding of logs but also in the transport of logging residues, and as such the issue of their efficient use should not be underestimated.

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