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**Increased fly ash utilization – value addition through forest road
reconstruction**

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Abstract

Increasing forest bioenergy utilization is increasing the need to discover more applications for fly ash to avoid dumping charges. Our study concentrates on defining the work phases of reconstruction work and estimation of construction costs for method where was used biomass based fly ash. Cost calculations were carried out for two mixed structures of fly ash and aggregate, two uniform structures of fly ash, and a conventional aggregate structure, where construction material volumes were calculated per kilometer for each structure. Our study defined suitable machines and their productivity per hour for different work phases. Cost calculation equations were formed for the used machines and the transportation of construction materials. Our study showed that building a 250-mm thick uniform layer of fly ash was the best alternative for minimizing construction costs. However, building a 500-mm thick uniform layer of fly ash was the best alternative for minimizing dumping charges.

Keywords: forest road construction, reconstruction, cost estimation, fly ash structure, rehabilitation

1 Introduction

Forest road trafficability is essential for successful wood procurement, which requires an adequate forest road system for on-time delivery of timber haulages. The criterion for technical validity can be decided upon based on the capability of maintaining trafficability throughout the seasons, especially during the spring thawing period. Special attention should be paid to the reconstruction of Finnish forest roads, because their technical conditions often restrict haulage at certain times. The planning and construction of new forest roads are instead becoming more irrelevant. Reconstruction annually occurs on 3000–4000 km of forest roads in Finland, while the total length of forest roads is approximately 135 000 km. The total costs of forest road construction and reconstruction were ca. 45.8 million euros in Finland, or equivalent to 12 400 euros per reconstructed kilometer in 2013. A new road construction cost actually provides slightly higher costs than those mentioned above, while the reconstruction cost offers a cheaper rate than mentioned. Finnish forest roads were mainly constructed between 1960 and 1990. As a consequence of aging, the service life of forest roads will be expiring soon. The costs of reconstruction are therefore expected to increase in the future (Metsätilastollinen vuosikirja 2014).

Increased fly ash utilization has potential benefits from the economic point of view. Dumping charges have risen lately in Europe, especially in Finland to €70 per ton. As a result of rising dumping charges, new applications or methods for utilizing fly ash have become more relevant. One third of the ash produced in Finland still ends up in landfills (Ojala 2010). Our study thus focused on fly ash, which is a by-product of burning wood and peat sources in the power plants of pulp mills. Fly ash biomass is hereafter referred to as FA in this paper. The power plants of forest industry and the heating plants of communities are the largest sources of ash. The quantity of ash is generally increasing, as a result of growing bioenergy use. Increased FA utilization (e.g. in forest roads) could achieve notable financial savings. In

addition, FA utilization employs earthmoving and transportation entrepreneurs and saves natural stone resources. The FA has several special characteristics. Based on grain size classification it is parallel to silt. FA structure is therefore a non-frost-resistant material with poor bearing capacity. Instead, the FA has high bearing capacity, when structure is compacted. FA contains calcium oxide, which strengthens due to optimum water content and compaction work (Tuhkarakentamisen käsikirja 2010). For these reasons the technical properties of FA differ from natural stone materials.

Forest road maintenance costs comprise an approximately 10% share of the total forestry costs (Piiparinen 2003). The key aim of forest road construction and maintenance is to minimize timber transport costs without jeopardizing the logistics of wood procurement. Forest roads can be built or repaired to correspond with year-round traffic, if this is necessary for wood procurement. The technical upgrading of forest roads is not an obstacle for such construction or reconstruction work, but rising costs are. If these costs are high, the cost-effectiveness of investment is not actualized, because the achieved financial benefits from harvesting, transportation or other forestry operations do not cover all the expenses. The challenge of the above-mentioned situation is the accurate estimation of construction costs to enable rationalized decision-making. The so-called bottom-up approach in forest road construction and cost modeling would deliver useful information for this decision-making.

Conventional forest road reconstruction has generally used certain types of sieve size gravel or crushed rock (aggregate). Wood- and peat-based FA is one novel material that has been studied in recent years (Kaakkurivaara et al. 2016; Bohrn and Stampfer 2014). These studies presented that FA significantly improved the bearing capacity of forest roads. However, results concerning the economic efficiency of forest road systems have not been published so far. Kumar and Patil (2006) studied FA profitability on public roads, where results showed that FA construction could reduce the demand for conventional construction materials and

transportation. This means that using less conventional construction materials decreased the total costs. The modeling tool for prioritizing the reconstruction procedure for forest road networks has been made for the purpose of improving accessibility to spring thawing - qualified harvest sites (Olsson and Lohmander 2005). However, minimizing the actual costs of construction operations does not help the situation. The work phases of forest road construction have been described by Ghajar et al. (2013). Nevertheless, their cost calculation model does not contain those work phases that would be usable for FA reconstruction. Generally actualized cost prices have been reported widely for the different work phases of forest road construction in North America (Balcom 1988; Conrad et al. 2012; Cost estimating... 2011; Kochenderfer et al. 1984). Results of these studies cannot be utilized by our study, because cost information is confined to time and place. No ready-made cost calculation models were available for FA construction on forest road systems. The special characteristics of FA complicate this research topic, as FA requires certain types of treatment and construction techniques.

Many previous forest road cost studies have focused on the cost minimization of new forest road network planning and construction (Akay 2003; Akay and Sessions 2005; Abdi et al. 2009; Ghajar et al. 2013). These studies focused more on the effects of forest road location in relation to construction costs, but different road materials were not compared. As mentioned above, a certain demand exists for cost calculation models that can be applied for estimating the economic performance of forest road construction, maintenance, and repair. The modeling should also take road material selection into consideration. Generally, the basic idea of cost calculation is to identify and determine all relevant factors that incur costs to the cost objects. Cost factors are usually divided into variable and fixed costs. Variable costs are e.g. raw material, fuel, and tire costs, whereas capital, interest, and annual depreciation represent fixed costs. Furthermore, labor costs are usually handled as a separate cost factor

(Sessions and Sessions 1992). When all cost factors are determined and summed together to obtain the total costs they must be allocated to the calculation objects. These calculations must be made for each relevant process and road material for thorough economic evaluations and comparisons. Using cost modeling instead of merely relying on statistical average values also provides better possibilities for finding causal connections that may otherwise remain hidden.

The aim of our study was to develop a cost calculation model for reconstruction and estimate the economic aspect for utilizing FA on forest road circumstances. The four test structures from FA and the reference structure from the aggregate were established for calculation. This included definitions for the work phases, workable machines, and their output per hour. The target of our study was to compare economic efficiency between test structure types to regulate reconstruction and seek an opportunity for minimizing costs at landfills.

2 Material and methods

2.1. Study procedure

The cost calculation for FA utilization is a logical continuation of a prior study regarding forest road bearing capacity improvement with test structures (Kaakkurivaara et al. 2016). Four test structure types were used in the above-mentioned study, which included two uniform FA test structure types and two FA test structure types mixed with an aggregate. A description of the construction work was divided into work phases, which were attached to suitable earthmoving machines. Total cost calculation formulas were created for uniform, mixed, and reference test structures, which included machines and construction materials. Costs per hour were calculated for each machine. Machine outputs were either measured during the above-mentioned study or manufacturer-provided values were used. FA and aggregate quantities were calculated as units of volume and converted to a mass unit for

every test structure type. Construction costs for every test structure type were calculated based on these values per kilometer. Our study used regular reconstruction, containing the aggregate for comparison, to increase bearing capacity.

2.2. Test structure types

The FA was used on four different test structures, which were compared to a regular reconstruction structure. The cost calculation excluded some repair phases of old roads such as grading and improving drainage. These costs depend on the condition of the initial road and hence the issue is not relevant for this particular calculation. The test structures used in our study were assumed to be built on top of old roads, as executed by Kaakkurivaara et al. (2016).

A regular reconstruction structure was used as a reference structure. It contained a 200-mm thick aggregate layer with grain sizes between 0 and 32 mm. Justification for regular structure is the following. Test road sections, which were established in the above-mentioned study, had detected an approximately 50-MPa bearing capacity value measured by a light falling weight deflectometer from a wheel path. The Finnish Transport Agency has set a target value of 80 MPa for the bearing capacity of gravel roads (Finra 2004). Finnish guidelines for forest roads are presented in forest road publication, which helps scale the addition of the aggregate layer to reach target values (Metsätieohjeisto 2001). The addition is possible to determine when the initial bearing capacity level is known. Elastic modules of aggregate were presumed to be 150 MPa, which is a typical rate for crushed rock. The guideline figure showed that addition of the aggregate needs to be 200 mm to reach the target value in this case.

The FA was utilized in four different test structures; in two of the structures it was mixed in with the aggregate, while being built into the uniform structures of the other two. All of the

test structures were also paved with the aggregate. The structures were based on loose cubic meters of construction materials, when the eventual structure volume was smaller. The following densities during transportation and building were used in the calculations: 1100 kg/m³ for FA and 1540 kg/m³ for aggregate prior to compaction work. The final thickness of the FA structures was calculated with a 66% compaction rate (Tuhkarakentamisen käsikirja 2012; Raiku webpage).

FA and aggregate quantities are presented in Table 1 for each test structure. These values can be presented using round numbers to aid in understanding the magnitude of quantities for later use. Forest road width was 3.6 meters, and values were always presented in kilometers. The quantities given in Table 1 were calculated based on Table 2, where the test structures were defined based on construction layer volumes and thicknesses in loose cubic meters. The idea of test structures #1 and #2 was to increase bearing capacity by the joint effect of the FA and aggregate. The aggregates are comprised of more coarse-grained material than the FA, while the FA has solidified features. Together these would afford more bearing capacity for forest road structures. The materials of test structure #1 were mixed in a ratio of 1:2 (FA : aggregate), when the total layer thickness was 150 mm. The FA and aggregate were mixed together in equal portions in test structure #2, where the total thickness of the construction layer was 200 mm. The thickness of the uniform FA layer was 250 mm and 500 mm in test structures #3 and #4, respectively. A 100-mm thick aggregate layer covered all the test structure types, which was a precondition for gaining environmental permission. Test structure thickness decreased as a consequence of compaction.

2.3. Definitions of work phases and machinery productivity

Accurate definitions were given to various work phases and work hour productivities for the applicable machines. The definitions were collected in Table 3 of this study. Selecting

techniques applicable with readily available machinery was the aim when defining the work phases for our study. These machines were a wheel loader, excavator, motor grader, and vibratory roller. A wheel loader was used for loading the FA and aggregate, the bucket size of wheel loader was 3 m³. Wheel loader productivities per hour are presented in the South African forest road handbook (2005). This publication was used as a source for the productivity rates: FA was estimated to be a very easy material for loading (216 m³/h), while the aggregate was estimated as medium (144 m³/h). Table 3 presents the hourly productivity of the central mixer (200 m³/h) related to mixing the FA and aggregate together. The ratio has been expressed in parenthesis, because the rate has only been used to estimate transport equipment requirements. Productivity of the central mixer assessed the need to have four tip trucks with a gross weight of 76 tons deliver mixed materials directly for utilization. A wide variety of various mixers is available on global markets, and therefore using the same cost calculation model process as with other machines is not essential. Calculations have been simplified using the developer/entrepreneur's price per ton. The excavator and motor grader have been used for construction work for test structures #3 and #4, which the measured data were collected (Fig. 2). Productivities for the vibratory roller and motor grader were originally from the manufacturers. For operation they recommended an approximately 19-ton motor grader for grading and an approximately 8-ton single drum vibratory roller for compaction work of the construction layers.

2.4. Cost factors and cost calculation models

2.4.1. Machinery

The most important and interesting costs in our study occurred during various work phases on the forest road, which were related to the FA test structures. Cost calculation for machinery was included in three main categories: (i) fixed costs, (ii) operational costs, and (iii) labor

costs, where the two latter were variable costs. Machine cost factors were collected from the sales departments of machines and entrepreneurs who were involved in reconstruction operations. The cost factors of all four machines are presented together in Table 4. Machine costs were calculated per working hour.

Same cost calculation equations can be utilized for every machine to calculate the cost per hour in our study. The implemented equations for the calculations are presented in equations 1–6. The fixed costs for using earthmoving machines compound from (a) annual interest cost (Eq.1), (b) depreciation cost (Eq.2), and (c) other miscellaneous costs. The miscellaneous costs included insurances, fuel, tires, repair and maintenance, and transfer costs. Tire service life was dictated as a constant three years for all machines. Total machinery costs are summed up in Equation 3 as far as they have been taken into consideration during our study. Abbreviations of all following equations are detailed in the Appendix of this article.

Annual interest cost:

$$[1] \quad AC_{int} = \frac{Int}{100} * \frac{PP+SV}{2}$$

Straight-line annual depreciation:

$$[2] \quad AC_{dep} = \frac{PP-SV}{SL}$$

Total annual machinery costs:

$$[3] \quad AC_{mac\ tot} = AC_{int} + AC_{dep} + AC_{ins} + AC_{fuel} + AC_{tyre} + AC_{rep} + AC_{transp}$$

Variable machine costs depend on annual utilization hours, including labor and operation costs. Annual labor costs were defined in Equation 4. In labor costs indirect costs such as

social security costs and traveling and meal compensations were taken into account. Overhead costs (Eq. 5) covered other costs such as accounting company, rent, and communication devices. Equation 6 presents the annual total cost for earthmoving machines. It also included annual risk and the surplus target for business. The target of the calculation process was to obtain total costs for the operational hour, which is the annual total cost, divided by the annual utilization time (Eq. 7). The outcome of this cost calculation expressed expenses in euros per hour, when business is profitable.

Annual labor cost with traveling expenses

$$[4] \quad AC_{lab} = WH * WC + \left(WH * WC * \frac{IWC}{100} \right) + AC_{tr}$$

Overhead costs

$$[5] \quad AC_{overh} = \frac{OHC}{100} * \left(\sum_1^{n_{lab}} AC_{lab} + AC_{mac\ tot} \right)$$

Annual total costs

$$[6] \quad AC_{tot} = \left(1 + \frac{A_{rs}}{100} \right) * \left(AC_{mac\ tot} + \sum_1^{n_{lab}} AC_{lab} + AC_{overh} \right)$$

Total cost for operational hour

$$[7] \quad HC_{tot} = \frac{AC_{tot}}{WH}$$

2.4.2. Trucking

Earthmoving work may have a significant role in road construction, when material must be transported outside the construction area. Earthmoving work normally occurs when soil quantity or quality is not adequate for the planned road structure. Certain aspects of the

transportation costs constitute an exception from the above-mentioned machinery costs, although the basic principle is the same. Cost factors were either time- or distance-dependent. This grouping was also used for the tip truck in Table 5. Time-dependent costs were based on the actual time consumption of transportation, whereas distance-dependent costs included fuel consumption, maintenance service, and tire costs. Fuel consumption was formulated in Equation 8, where half of the driving distance was assumed to be unloaded and the other half was driving with a load. The tire cost situation was more complex for the tip truck than the machines. Because of varying prices and the number of tires used in the truck tractor and trailer, and the possibility of remolding, tire costs were formulated in Equation 9 to calculate annual cost. These equations were used together with Equations 1–6 to calculate total annual costs.

Fuel costs for the tip truck and trailer were calculated with the following equation:

$$[8] \quad AC_{fuel\ tr} = \frac{FCN_{tr\ L} * D_L * PF_{tr}}{100} + \frac{FCN_{tr\ E} * D_E * PF_{tr}}{100}$$

The tire costs (€ per year) of a tip truck and trailer were calculated with the following equation:

$$[9] \quad AC_{tire} = AD * \left[N_{tr\ tire} * \left(\frac{PR_{tr\ tire} + TRM * PR_{rm\ tire}}{SL_{tire} * (1 + TRM)} \right) + N_{tl\ tire} * \left(\frac{PR_{tl\ tire} + TMR * PR_{rm\ tire}}{SL_{tire} * (1 + TRM)} \right) \right]$$

Calculating costs per hour was necessary for the machines in our study. Calculations for the tip truck were necessary to gain information on costs per kilometer (Eq. 10), where the annual utilization time was assumed to be 55 000 km. The cost per transported ton depended on results of the transported cargo mass and driven kilometers, which have significantly influenced the outcome (Eq. 11).

Costs of the tip truck and trailer per driven kilometer (€/km) were calculated as follows:

$$[10] \quad C_{tr\ km} = \frac{AC_{tot}}{AD}$$

Costs per cargo mass of the tip truck and trailer were calculated with the following equation:

$$[11] \quad C_{tr\ mass} = \frac{C_{tr\ km} * D_{sid}}{M_{tr}}$$

2.5. Other cost factors

The central mixer was used for mixing the FA and aggregate for test structures #1 and #2. The mixing process can be executed in various ways depending on the available machines and material quantities. No particular formulated equation was therefore applied for the mixing in our study. We used a price of €6 per ton for the mixing, which also included FA and aggregate input and reloading of the mixed materials. Machinery was modified from an asphalt-mixing machine made by an asphalt contractor. The mixing process was carried out at a quarry, where the FA was transported. The material cost of aggregate was defined rather typically as €5 per ton.

Driving distances used in the field study were also used in the calculations (Fig. y1). Back and forth distances for the FA and aggregate were 50 and 20 kilometers, respectively. The mixing was assumed to take place at the quarry, where the FA transportation distance was the difference between the above-mentioned distances divided by two, i.e. 15 km. The cargo mass per ton depends on the density of the transported material and the load capacity size. Cargo mass was 39 tons for the FA and 49 tons for the aggregate, which are based on materialized values from the field. A rough estimation for the mixed material was 44 tons per cargo. The transportation distance and cargo mass have significant influence on transportation costs.

These effects are case-specific, i.e. the direct use of the calculated results cannot be used to directly recommend their use during other circumstances.

2.6. Total construction cost formulas for test structures

Equations 1–11 were used in each relevant addend in Equations 12–14. For total construction costs, we defined the material quantities (ton/km) of each test structure, the machine productivities of different work phases (km/hour), and the total operational hour costs for each machine (€/hour). Exact costs (€/ton) for every work phase can be calculated by multiplying together these cost factors for each construction work phase in each of the test structures. This value can further be multiplied with the material quantity of the test structure (ton/km) when the final result is given in euros per kilometer. Adding other costs, such as material costs (€/ton) and mixing (€/ton), can be used to create total cost formulas for construction work sorted by construction techniques:

Mixed structures (#1 & #2):

$$[12] \quad C_{\text{Total}} = C_{\text{FA loading}} + C_{\text{FA transport}} + C_{\text{Aggregate}} + C_{\text{Mixing}} + C_{\text{Mix transport}} + C_{\text{Grading}} +$$

$$C_{\text{Compact}} + C_{\text{Surface Aggregate}} + C_{\text{Aggregate Loading}} + C_{\text{Aggregate transport}} + C_{\text{Final grading}}$$

Uniform structures (#3 & #4):

$$[13] \quad C_{\text{Total}} = C_{\text{Sidebarriers}} + C_{\text{FA loading}} + C_{\text{FA transport}} + C_{\text{Spreading FA}} + C_{\text{Grading FA}} + C_{\text{Grading}}$$

$$\text{slopes} + C_{\text{Compact FA}} + C_{\text{Surface Aggregate}} + C_{\text{Aggregate Loading}} + C_{\text{Aggregate transport}} + C_{\text{Final gradin}}$$

Regular structure (20 cm):

$$[14] \quad C_{\text{Total}} = C_{\text{Aggregate}} + C_{\text{Aggregate Loading}} + C_{\text{Aggregate transport}} + C_{\text{Final grading}}$$

3 Results

Working hour costs for all four machines are presented in Figure 3. Because of reasonable purchase prices for the wheel loader and vibratory roller, their working hour costs remained at the lowest level, 56.8 and 55.9 euros per hour, respectively. The calculation outcome for the excavator was 60.6 euros per hour. The motor grader had the highest purchase price and its working hour costs were also the highest, at 82.4 euros per hour. These cost values appear to be realistic compared to general pursuit prices for earthmoving services. A relatively low 3% provision was used for the risks and surplus target for business, which affect the outcome. These costs of working hour values are reliable for further use to compare test structures with regular structures in our study. The utilization times of a vibratory roller and a motor grader were estimated at six months per year, but capital costs were counted for the entire year. The low utilization time led to higher hourly machine costs. Instead, the excavator and wheel loader were assumed to be fully utilized.

Cost calculations were carried out for all used construction materials considering the total quantities, transport distances, and cargo masses (Fig. y4). Despite the generalization of the cost calculation model, the outcome is rather suitable and reliable for estimating forest road reconstruction costs. The construction materials were transported by a tip truck with a gross weight of 76 tons. The annual service time for the tip truck was low (55 000 km). This figure was the same for all transportation schemes used in the calculations, despite transportation distances differing. Transportation costs for the FA were approximately three times more expensive (3.37 €/ton) than for the aggregate (1.07 €/ton) or mixed material (1.19 €/ton).

The main results of our study are presented in Table 6, where structure costs were of the same order as defined in the total cost formulas. The reference structure for comparison was rehabilitated with a 200-mm thick aggregate layer (Regular). An approximately double-sized

difference was observed between the cheapest (Regular) and most expensive (#2) structures. Comparing the FA structures with the regular, structures #1 and #4 were observed to be approximately 70% more expensive. The most inexpensive way of utilizing FA was #3, which had total costs of only 23% higher than the regular. The mixing processes of the FA and the aggregate were the most notable work phases for test structures #1 and #2. Their total cost shares were approximately 36 and 38 percent, respectively. Aggregate material costs were also similarly notable for #1 and #2, being approximately 43 and 37 percent of the total costs, respectively. The transportation of FA was the most expensive work phase for structures #3 and #4. Generally speaking, grading was the cheapest work phase, performed by the motor grader in every test structure. Either the loading or the compaction of FA did not incur remarkable costs.

Test structure #3 on the forest road was the most economical option. Losing the opportunity of utilizing FA will cause an opportunity cost because the dumping charge is €70 per ton in Finland. The most cost-efficient test structure (#3) needed approximately 990 tons of the FA per km (Table x1), where construction costs were 8953 euros per km (Table 6). Cost savings were 60 347 euros per km when dumping charge and the quantity of FA per km were multiplied together and construction costs were removed. The cost savings only concern this calculation, but generally the cost savings decrease when FA transportation distance increases. Machinery costs are not affected if the transportation distance is changed. This rule applies with one condition: aggregate must always be available at a 10-km range from the road under reconstruction.

4 Discussion and conclusions

Our study contained three stages: material quantity calculations for each test structure, a definition of the work phases and productivities for suitable machines, and a calculation of

the total costs per operational hour for every machine. These three stages helped to estimate FA utilization from an economic point of view. The FA test structures were the same as those used in a study by Kaakkurivaara et al. (2016). The structures deviated from each other on the grounds of FA and aggregate quantities. Due to these differences, the costs also deviated between the test structures. However, cost differences were not tenfold between the test structure types. Based on this fact, our results can be assumed to be successful and comparable between each other. However, the cost levels are not equal throughout the world. They depend on time and the place where the reconstruction of forest roads is executed.

Construction material quantities were founded on loose cubic meters to calculate test structure volumes. The meaning of this action was illustrated using material quantities. The utilized FA quantities concurrently also became rather explicit: 200 (#1), 400 (#2), 1000 (#3) and 2000 (#4) tons per kilometer. This makes it easier to estimate the need of FA for different forest road lengths. In other words, these values illustrate the maximum length of forest road that is possible to renovate with a certain amount of FA. Moreover, the FA worked as expected. The initial thicknesses of the construction layers have reduced approximately one third from the original thickness, which responds very well with the compaction ratio found in the literature (Tuhkarakentamisen käsikirja 2012).

It was possible to split the FA structures into two different categories: FA mixed with aggregate and uniform FA structures. Work phases can also be defined according to this split. The principle is to find universal and reliable machines, with measurable or predictable productivities. This action guarantees the global utilization of our study. Both work phase procedures include the same machines as much as possible during similar work phases. An exception to this is the grading work carried out on the uniform FA structure; the field experiment showed that the work had to be carried out using a time-consuming excavator

instead of a motor grader. From Table 6 it is easy to see the remarkably lower cost level for the motor grader, which is mostly based on the grader's faster working method.

The utilization of FA included work phase costs for forest roads. Earthmoving entrepreneurs did not provide this information for public use or alternatively no published time studies exist. It was therefore not possible to choose the general average cost for machine work. The FA and aggregate mixing process was the only direct price received from the entrepreneur that was used in the calculations. However, gaining precise information on price formation is not possible if the cost factors cannot be collected. There are two notable observations concerning the cost calculations. The cost calculations for machines were defined as rather low, three percent profits for an entrepreneur. A higher utilization rate of the machines would have a positive effect on the costs, in which case the modification would act against any information given by the entrepreneur. Our study presents the cost calculation model for the machinery and transportation, not only for this particular study, but also for the further use of forest road construction and reconstruction.

Costs per hour equations for the machines follow the general principals of cost calculations, which were also used in other studies such as Nurminen et al. (2009). The cost factors and source information of the equations may involve inaccuracies or shortages from certain parts. The impact of these on the big picture is rather minor because the calculation includes several different cost factors. Machine cost comparisons can detect great influences on the final value of hourly costs through the purchase price, service life, and annual utilization time. It is important to remember that entrepreneurs may not charge equivalent prices to customers as those presented in Figure 3.

It was necessary to analyze the trucking costs in a separate section, because the cost calculation model contained both time-dependent and distance-dependent costs. The average

transport distance and number of truck loads per year restrict the maximum annual utilization time of the tip truck. The utilization time may roughly adjust with daily driving speeds to reach a realistic level based on average distance and the number of truckloads per working day. This condition is considered to be fulfilled in our study. Price setting of the trucking service depends in practice on the transported distance, because gross weight normally remains at the highest permitted level. The trucking costs in our study were especially affected by both transportation distance and cargo mass, which caused differences in the results in Figure 4. It is not justifiable to compare values from Figure 4 with actual prices, which were charged from customers by the entrepreneur. Trucking cost formation has been described as thoroughly as possible based on the cost factors provided in our study. To summarize all the facts above, it is justifiable to presume that calculated work phase costs for reconstruction work on forest roads are applicable. The main target of our study was to compare the costs of various FA structures between each other and the regular structure. The target was not to present actual machine costs per hour, although it is possible to use the presented cost equations in later studies.

The total cost per rehabilitated kilometer was €7305 for regular aggregate use and 8953–14 839 euros for the FA structures. A good point of comparison is the statistical average (€12 400 per kilometer), which includes reconstruction and construction costs in Finland (Metsätalastollinen vuosikirja 2014). When this statistical cost price is compared to the total costs of the test structures, the outcome of our study can be observed to be very reasonable. This is particularly true in cases where our study ignored costs from the preliminary work phases of reconstruction, planning, and supervision. FA utilization can be considered a reasonable choice for the reconstruction of forest roads instead of the regular use of aggregate in certain conditions.

The cost calculation results showed FA utilization to be more expensive than the mere aggregate. This is not a surprising result because the total construction material quantity and the number of work phases were clearly greater than with regular reconstruction. The results were actually surprisingly positive, in that the total cost differences were not wider than those in Table 6. In practice, the cheapest FA structure (#3) is also fairly similar as during a scenario where an entrepreneur adds an approximately 300-mm thick layer of FA on top of an old road before compaction work and paves it using the aggregate. This proves that hand-on practice and theoretical methods end up with the same conclusion, which also supports the results of our study. It is important to remember that the test structures do not contain other reconstruction action costs e.g. drainage improvement. On the other hand, these test structures included improvement materials for bearing capacity and road grading, which is a common action during forest road reconstruction.

Result significance is highlighted when cost savings were calculated using the dumping charges. If fly ash is suitable from the technical point of view and harmless to the environment, it is possible to reach substantial financial benefits. The greatest possible quantity of fly ash used in forest road reconstruction reduces most of the dumping charge costs. In this situation, test structure #4 is the best of all the proper choices. If annually produced fly ash can be utilized completely for different applications, it is more important to minimize the utilization process costs. The conclusion of our study is that from the economical point of view the best choice is test structure #3. In the future it is necessary to continue developing the construction techniques to make them more cost-effective. To enable more frequent fly ash construction, cost competitiveness should catch up with regular structure costs.

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Draft

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Table 1. Fly ash (FA) and aggregate (Agg.) quantities estimated depending on weight (tons per km) for regular and test structure types. Parentheses express round values for materials.

	FA	Agg. for mixing	Surface Agg.	Total
#1	198 (200)	554	554	1307 (1300)
#2	396 (400)	554	554	1505 (1500)
#3	990 (1000)	-	554	1544 (1500)
#4	1980 (2000)	-	554	2534 (2500)
Reg.	-	-	1109	1108 (1100)

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Table 2. Fly ash (FA) and aggregate (Agg.) quantities presented by thicknesses and volumes for regular and test structure types.

	FA	Mixed Agg.	Surface Agg.	FA	Agg.	Total
	Thickness, m			Volume, m ³ /km		
#1	0.05	0.1	0.1	180	720	900
#2	0.1	0.1	0.1	360	720	1080
#3	0.25	-	0.1	900	360	1260
#4	0.5	-	0.1	1800	360	2160
Reg.	-	-	0.2	-	720	720

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Table 3. Defined work phases and machines for the reconstruction work for test and regular structure types presented with their productivities per hour. Column 'Place' specifies work phase location, i.e. whether work occurred on-site or outside of a rehabilitated forest road.

Blank boxes for the tip truck indicated that specifying productivity per hour was not possible.

Sources: [1] own field studies; [2] South African forest road handbook, and [3] manufacturer.

	Work phase	Place	Machine	Productivity	Unit	Source
Test structures #1 and #2						
1	FA loading	outside	Wheel loader	216	m ³ /h	2
2	FA transport	outside	Tip truck			
3	Mixing	outside	Central mixer	(200)	m ³ /h	3
4	Mix transport	outside	Tip truck			
5	Grading	on-site	Motor grader	3.750	km/h	3
6	Compact	on-site	Vibratory roller	240	m ³ /h	3
7	Aggregate Loading	outside	Wheel loader	144	m ³ /h	2
8	Aggregate transport	outside	Tip truck			
9	Final Grading	on-site	Motor grader	3.750	km/h	3
Test structures #3 and #4						
1	Side barriers	on-site	Motor grader	0.250	km/h	1
2	FA Loading	outside	Wheel loader	216	m ³ /h	2
3	FA transport	outside	Tip truck			
4	Spreading FA	on-site	Excavator	0.083	km/h	1
5	Grading FA	on-site	Excavator	0.250	km/h	1
6	Grading slopes	on-site	Excavator	0.250	km/h	1
7	Compact FA	on-site	Vibratory roller	240	m ³ /h	3
8	Aggregate Loading	outside	Wheel loader	144	m ³ /h	2
9	Aggregate transport	outside	Tip truck			
10	Final grading	on-site	Motor grader	3.750	km/h	3
Regular structure						
1	Aggregate Loading	outside	Wheel loader	144	m ³ /h	2
2	Aggregate transport	outside	Tip truck			
3	Final grading	on site	Motor grader	3.750	km/h	3

Table 4. Cost factors for a 22-ton excavator, 19-ton motor grader, 8-ton vibratory roller, and 130-kW wheel loader. Costs are given excluding value-added tax (VAT). Prices are based on the situation in Finland in 2015.

	Cost factor	Excavator	Motor grader	Vibratory roller	Wheel loader	Unit
Fixed costs	Purchase price of machine	17 5000	35 0000	67 000	145 000	€
	utilization time	1760	880	880	1760	h/a
	Service life in years	5	20	5	5	a
	Resale value, remaining share of purchase price	35	10	35	35	%
	Demand of own capital	30	30	30	30	%
	percentage of interest for own capital	3	3	3	3	%
	percentage of interest for borrowed capital	5	5	5	5	%
	Insurances	1800	500	250	350	€/a
	Overheads (Fixed+Operational+Labor)	5	5	5	5	%
	Provision for risks and surplus target	3	3	3	3	%
Operational costs	Fuel consumption	12	22	8	11	l/h
	Fuel price	0.75	0.75	0.75	0.75	€/l
	Transfer costs	7500	-	4000	4000	€
	Maintenance costs	2.22	3.6	2.0	2.52	€/h
	Tire costs, service life 3 years	-	1472	2902	2238	€/a
Labor costs	Hourly wage	14.2	14.2	14.2	14.2	€/h
	Amount of workers	1	1	1	1	Person/machine
	Duration of working day	8	8	8	8	h/day
	Quantity of working day	220	110	110	220	days/a
	Indirect wage costs	65	65	65	65	%
	Travel and daily allowance	2000	2000	2000	2000	€

Table 5. Cost factors for a tip truck (a five-axle, 8x4 power configuration and a four-axle trailer. The total vehicle mass limit was 76 tons).

Cost factor		
Time-dependent costs	Value	Unit
Purchase price of tractor	235 000	€
Purchase price of trailer	85 000	€
Service life in years, tractor	5	a
Service life in years, trailer	10	a
Utilization time	55 000	km/a
Resale value, tractor	35	%
Resale value, trailer	10	%
Demand of own capital	30	%
percentage of interest for own capital	3	%
percentage of interest for borrowed capital	5	%
Insurances	4500	€/a
Taxes and safety inspection	2000	€/a
Hourly wage	13.8	€/h
Amount of workers	1	person/machine
Indirect wage costs	65	%
Duration of working day	8	h/day
Quantity of working day	220	days/a
Travel and daily allowance	500	€/a
Overheads (=fix & var. C.)	5	%
Provision for risks and surplus target	3	%
Distance-dependent costs		
Fuel consumption, loaded	55	l/100km
Fuel consumption, empty	46	l/100km
Fuel price	0.95	€/l
Maintenance costs	5640	€/a
Number of tires, tractor	14	pcs
Number of tires, trailer	16	pcs
Tire service life	80 000	km
Tire price, tractor	809	€/pcs
Tire price, trailer	467	€/pcs
Remold price	250	€/pcs
Number remolds during service time	1.5	pcs/tire

Table 6. Cost of the reconstruction methods are divided into forest road work phases, when the construction material has been: a mix of fly ash (FA) and aggregate (Agg.) in test structures #1 and #2, a uniform fly ash construction layer in test structures #3 and #4, or a conventional use of aggregate in the regular test structure. The utilized equations are presented in brackets. The unit is euros per km.

Costs	#1, [12]	#2, [12]	#3, [13]	#4, [13]	Regular, [14]
Sidebarriers			330	330	
FA loading	52	104	260	520	
FA transport	667	1335	3336	6673	
Aggregate	2772	2772			
Mixing	4514	5702			
Mix transport	895	1131			
Spreading FA			727	727	
Grading mix/FA	22	22	242	242	
Grading slopes			242	242	
Compact of mix/FA	126	168	209	419	
Surface agg.	2772	2772	2772	2772	5544
Agg. loading	219	219	219	219	552
Agg. transport	593	593	593	593	1186
Final grading	22	22	22	22	22
Total	12654	14 839	8953	12 759	7305

Figure 1. Transportation distances and cargo mass for construction materials.

Figure 2. Test structure #4 after slope grading by excavator before covering with surface aggregate.

Figure 3. Hourly cost for earthmoving machines based on the above-mentioned Equations 1–7 and cost factors in Tables 1, 2, and 4. The unit is euros per hour.

Figure 4. Transportation costs for construction materials based on the above-mentioned Equations 1–11 and cost factors in Tables 1 and 5. The unit is euros per ton.

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