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Model for cost calculation and sensitivity analysis of forest operations

S. Kalēja*, A. Lazdiņš, A. Zimelis and G. Spalva

Latvian State Forest Research Institute "Silava", 111 Rigas street, LV-2169 Salaspils, Latvia
*Correspondence: santa.kaleja@silava.lv

Abstract. Forest operations include logging, off-road and road transport of round wood, harvesting residues and wood chips, soil scarification and pre-commercial thinning, as well as other less conventional operations like stump extraction and undergrowth removal before felling. The process of harvesting can involve different interfering phases with specific productivity parameters, which will have impact on the productivity of harvesting and delivery, as well on the prime cost of logs and forest biofuel. Detailed prime cost calculation allows to assess the impact of various factors on costs of the products, as well as to define threshold values for certain parameters affecting the productivity. The base model elaborated within the COST action FP0902 is complemented with standard economic methods and adopted to the harvesting process or any other forest or farming operation including systems consisting from several machines. The model is designed in a way, which is simple in use, easily extensible with additional parameters and machines and with possibility to change individual input data. The cost calculation section of the model consists from investments (base machines and equipment), labor costs (salaries, social charges, insurance and other payments) and operational costs (fuel, lubricants, maintenance, repair and other consumables). The average hourly cost is calculated according to forecast of number of working hours per year. Engine hours are used in calculation to synchronize input data with service statistics from dealers' centers. The parameters of the forest stands affecting productivity, like diameter or volume of an average extracted tree, number of relocations per year, average off-road transport distance, driving speed and other parameters are defined in the calculation. Productivity and load size can be set as fixed values or equations (in case if the sensitivity analysis should be done). The model calculates the hourly cost (productive, engine and proposed working hours) and the unit price for each phase of the work process. The sensitivity analysis demonstrates impact of various factors, like number of working hours per year, dimensions of the average extracted tree, forwarding and road transport distance, fuel price and fuel consumption as a default parameters or any other indicator, which can be added to the sensitivity analysis. The model is validated against the actual harvesting contracts and hourly cost of rental machines. Default parameters in the calculation are summaries of information provided by contractors or service companies.

Key words: cost calculation, forest operations, productivity.

INTRODUCTION

The harvesting process involves logging, off-road and road transport of round wood, harvesting residues and wood chips, as well as other less conventional operations like stump extraction and undergrowth removal before felling (Uusitalo, 2010; Sarmulis & Saveļjevs, 2015). This process can involve different interfering phases with specific productivity parameters, which will have impact on the productivity of the harvesting and materials' delivery, as well on the prime cost of logs and forest biofuel.

The prime cost of the harvesting is the total amount of utilized production resources expressed in monetary terms (Vītola & Soopa, 2002; Grīnfelds, 2004; Alsiņa et al., 2011). Detailed prime cost calculation allows to assess the impact of various factors on cost of the production, as well as to define threshold values for certain parameters affecting the productivity (Grīnfelds, 2004; Alsiņa et al., 2011).

Cost calculation models usually are complex tables consisting from the input and output sections. The input section of the model may consist from investments (base machines and equipment), labor costs (salaries, social charges, insurance, training and other payments), operational costs (fuel, lubricants, maintenance, repair and other consumables) and other input data, like productivity, characteristics of stands, forwarding and driving distance, road transport distance, average load size (FAO, 1992; Grīnfelds, 2004; Alsiņa et al., 2011; Ackerman et al., 2014). Production cost consists of direct and indirect costs. Direct production costs are directly related to creation of certain cost objects and depends from utilization rate of the machine or number of produced units. Generic or indirect production costs are not directly related to the production of the particular product but are conditionally linked to the production process and are included in the cost calculation of production using addition rate (Vītola & Soopa, 2002; Alsiņa et al., 2011). Determination and allocation of indirect costs by object of calculation is carried accordingly to the amount of production or period of production (Alsiņa et al., 2011). Output section of the cost calculation model usually represents hourly cost (productive, engine or proposed working hours) and the unit price for each phase of the harvesting process (Ackerman et al., 2014).

Sensitivity analysis is aimed on demonstration of impact of various factors, like number of working hours, dimensions of the average extracted tree, off-road and road transport distance, fuel price and fuel consumption or other factors.

Aim of this study is to create comprehensive cost calculation model, which can be used to evaluate multiple forest operations in different work conditions and to determine impact of changes in the system on the costs of production.

MATERIALS AND METHODS

The base model elaborated within the scope of COST action FP0902 (Ackerman et al., 2014) is complemented with standard economic methods and adapted for the harvesting process or any other forest operation including systems consisting from several machines.

The model is validated against actual harvesting contracts in state forests in Latvia and hourly cost of rental machines provided by the dealers' centres. The default utilization rate (engine hours per year) is also taken as average value of multiple machines utilized in state forests. Other default parameters in calculations are summaries of information provided by contractors, service companies or dealers.

Productivity data obtained in previous studies over the period 2013 to 2017 are used to create the default productivity equations for thinning and final felling in the prime cost calculation. To validate the model, it is assumed, that middle sized harvester (John

Deere 1270 with engine power 170 kW, boom max reach 10 m, operating weight 18 t and fuel consumption on average 12 L per E_{15}) with accumulating Moipu 300 felling head is used for harvesting. Middle class forwarder (John Deere 810 E with engine power 100 kW, operating weight 12.9 t, average load 7.9 m^3, max crane reach 8.7 m, fuel consumption on average 12 L per E_{15}) or larger forwarder (John Deere 810 D with engine power 86 kW, operating weight 11 t, average load 5.4 m^3, fuel consumption on average 12 L per E_{15}, with crane CF 1, max reach 8.7 m) is used for off-road transport of raundwood and harvesting residues. In validation of cost of roundwood delivery to the consumer logging truck (Volvo D13K with engine power 309 kW, average load 36.2 m^3, fuel consumption on average 18 L per E_{15}) with trailer and Loglift 96 S crane is used. In biofuel delivery scenario costs are validated against mobile chipper of biomass Bruks 1001 (engine power 336 kW, fuel consumption 68 L per E_{15}) mounted on a forwarder Timberjack 1410 (engine power 136 kW, fuel consumption on average 12 L per E_{15}) and truck Volvo D13K (engine power 309 kW, average load 90 bulk m^3, fuel consumption on average 18 L per E_{15}) with interchangeable containers is used to validate road transport cost of wood chips. The service costs, as well as default parameters for calculations are available from earlier studies (Kalēja et al., 2014; Lazdiņš & Zimelis, 2015).

It is also assumed in the model validation that the implemented forest operation is thinning in coniferous stand and conventional cut-to-length technology is applied.

Engine hours are used in calculation to synchronize input data with service statistics from dealers' centres. The engine hours are also used to synchronize all time elements in the calculation, respectively, it is mandatory parameter, which should be obtained during time studies.

Cost items of the calculation model include investment costs and labour costs (Brinker et al., 2002; Alsiņa et al., 2011; Ackerman et al., 2014). The purchase value of new machinery and equipment are used in the calculation by default, an example is shown in Table 1 (Uusitalo, 2010; Ackerman et al., 2014). Real figurea available from studies or provided by contractors are used to validate the model.

Table 1. Example of calculation of the investment costs

	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Base machine price, € per unit	350,000	250,000	171,429	246,000	185,714	171,500
Depreciation period, engine hours	25,000	20,000	20,000	19,000	14,000	20,000
Type of equipment	felling head	tracks	-	tracks	chipper	-
Price of equipment, € per unit	30,000	18,500	-	18,500	255,500	-
Depreciation period, engine hours	10,000	12,000	-	12,000	14,000	-

The time frame during which the machine productivity and operating costs are economically justified is defined as the economic life time and in the calculation model is expressed in working hours or years (FAO, 1992) which are synchronized with engine hours.

Equipment is considered as variable costs because depreciation period (in working hours) of the equipment can differ from base machine, respectively the equipment should be changed several times during life time of the machine (FAO, 1992; Ackerman et al., 2014).

Depreciation period (*C*) of machinery and equipment in years is calculated (Eq. 1) by dividing proposed working hours (economic life time) with the forecast of engine hours per year according to the productivity indicators (Brinker et al., 2002).

$$C = \frac{B}{SX} \tag{1}$$

where *B* – depreciation period in engine hours; *SX* – productive hours per year.

To calculate residual value (*E*, expressed as a percentage of the purchase value) of harvesters and forwarders after end of economic life regression Eq. 2 is used (Bright, 2004; Spinelli et al., 2011).

$$E = 0.836 - 0.281 \cdot ln(C) \tag{2}$$

where *C* – depreciation period in engine hours.

For other machinery and equipment it is assumed by default, that the residual value (*E*) will be 15% of the purchase value.

Depreciation of machinery and equipment, calculated on a straight-line basis, is gradually attributed to the production costs (Alsiņa et al., 2011).

The residual value (*F*) estimated as a share of the purchase value of the machinery or equipment, is characterized by the expected resale values of the machine at the end of the economic life (FAO, 1992; Spinelli et al., 2011, Eq. 3).

$$F = A \cdot E \tag{3}$$

where *A* – base machine price, €; *E* – residual value, %.

Cost factor (*G*) is expressed in %. By default 5% depreciation rate (*D*) is used in the model to determine the annual investment cost of machinery and equipment (Eq. 4).

$$G = \frac{(D \cdot (1 + D)^C)}{(((1 + D)^C) - 1)} \tag{4}$$

where *C* – depreciation period, years; *D* – depreciation rate, %.

Annual costs of base machine and equipment (*H*) are calculated using Eq. 5.

$$H = G \cdot (A - F) \tag{5}$$

Labour costs consists of basic and supplementary wage of operator's, employer's compulsory social contributions and operator's benefits like training and insurance cost (Grīnfelds, 2004; Ackerman et al., 2014).

In calculation of labour costs, the average gross salary rate of the industry operator is used. The calculation of the production cost includes the social tax paid by employer, which according to Latvian legislation is 24.09% (State Social…, 1997) and is calculated from the salary rate (Alsiņa et al., 2011). In salary calculation it is also possible to set operators' overtime with double payment rate (Labor Law, 2011).

Labour cost calculation also includes additional incomes, that means compensation for a travel to work (by default 0.2 € km^{-1}), daily allowance, by default 6.00 € per day (Procedures for…, 2010), trainings (186 € yr^{-1}) and other labour costs, like insurance and subsistence costs.

Relocation costs are considered for harvesters and forwarders using separate trailer and for chipper (and other machinery, if needed) on its own (by default trailer's speed is set to 40 km h^{-1}, relocation distance – 50 km in one direction and 50 moves per year.

The calculations also use indicators that characterize availability of the machine. The availability of the machine depends from time spent for repairs and maintenance (Uusitalo, 2010). By default availability is set to 80%. Working hours per year (SZ) of each machine are calculated using Eq. 6.

$$SZ = \big((11 \cdot 20) \cdot 80\%\big) \cdot SH \cdot SJ \qquad (6)$$

where SH – overtime per shift, hours; SJ – number of shifts per day.

Machine utilization rate shows the readiness of machine in productive work (Uusitalo, 2010) and by default this value is set to 85%. The last value differs a lot depending from working conditions and age of machines.

Productive working hours per year (SX) of each machine (except log truck and chip truck) are calculated using Eq. 7. Idle during machine movement is calculated by dividing the average machine movement distance (50 km) and average machine speed (40 km h^{-1}). Time for loading and unloading belongs to work time and is excluded from productive time. On average, machines are moved 50 times per year.

$$SX = (SV + SZ) \cdot 85\% - \left(\frac{50}{40}\right) \cdot 50 \qquad (7)$$

where SV – working overtime, hours per year.

In the calculations it is assumed that one unit of machinery is serviced by 2 to 3 operators working on average 8 hours per shift for 11 months a year (on average, 20 working days per month).

Operators' driving distance per year (on average 30 km in shift (SL)) to access felling site and to return home (SY) of each machine operator (except log truck and chip truck) is calculated using Eq. 8.

$$SY = SL \cdot 2 \cdot SJ \cdot \big((11 \cdot 20) \cdot 80\%\big) \qquad (8)$$

where SL – trip to work (on average), km in shift; SJ – number of shifts, pieces per day.

In calculation it is assumed that the average compensation for each machine operator (except log truck and chip truck) for a trip to work is 0.2 € per km but daily allowance is 6 € per person per day. Annually 186 € per person are spent for training. Also other labour costs (approximately 1,500 € per person annually) are included in cost calculation (except operators of log truck, chip truck and biomass chipper). The cost calculation includes personal insurance, 357 € per person per year.

Operational costs are variable costs and they are closely related to the work load. These costs include fuel, lubricants, hydraulic oil, repairs, regular maintenance, relocations and other variable costs not listed above. Price of item included in calculation of operating costs is variable and depends on the situation on the market.

Working hours (E_0) in calculations corresponds to engine hours. Productive working time (E_{15}) is obtained by subtracting non-productive delay time from engine hours. Yearly operational costs are calculated according to number of engine hours per year.

Table 2 shows examples of consumption of items included in operational cost calculation.

Table 2. Consumption of items included in operational cost calculation

	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Fuel, L LV m^{-3}	-	-	-	-	0.7	-
Fuel, L E_{15}^{-1}	12	12	18	12	68	18
Fuel, L 100 km^{-1}	-	-	45	-	45	45
Fuel of trailer, L 100 km^{-1}	45	45	-	45	-	-
Lubricant, g E_{15}^{-1}	60	18	15	45	15	
Lubricant for chain, g E_{15}^{-1}	170	-	-	-	-	-
Fungicides, g E_{15}^{-1}	3	-	-	-	-	-
Hydraulic oil, ml E_{15}^{-1}	100	47	25	100	10	-

In order to make the prime cost calculation more accurate and adaptable to different conditions, specific productivity indicators and equations are used, like average size of extracted tree, harvester productivity, forwarder and truck load volume.

The indicators of the forest stands affecting productivity, like diameter or volume of an average extracted tree, average off-road transport distance, driving speed and other parameters can be set in the calculation.

Driving time (min) of roundwood forwarder and forwarder of harvesting residues (RI') is calculated using Eq. 9.

$$RI' = \frac{RH}{RE} + \frac{RH}{RF} \tag{9}$$

where RH – driving distance (one way), m; RE – average speed of forwarder (loaded), m min^{-1}; RF – average speed of forwarder (unloaded), m min^{-1}.

Calculation of log and chip transport (RI'', min) is done using Eq. 10. In calculation it is assumed that average speed of log and chip truck is 40 km h^{-1}.

$$RI'' = \frac{(2 \cdot RG)}{40} \cdot 60 \tag{10}$$

where RG – driving distance (one way), km.

Time spent (RJ, min or min of E_{15}) for transportation of one load with roundwood or harvesting residues forwarder, or truck of log or chip is calculated using Eq. 11.

$$RJ = RA + RB + RI \tag{11}$$

where RA – loading time of forwarder, minE_{15} per load; RB – unloading time of forwarder, min E_{15} per load; RI – driving time, min.

Productivity (*RM*, expressed in m^3 per productive hour or *RN*, loose volume (LV) m^3 per productive hour) and load size (*RL*) can be set as fixed values or calculated using Eq. 13 or 14 (in case if the sensitivity analysis should be done).

$$RM = \frac{RL}{RK} \tag{12}$$

where RL – average load, m^3; RK – time per load, hours. E_{15} per load.

$$RN = \frac{RL}{RK \cdot 2.4} \tag{13}$$

To transfer solid cubic meter into loose volume (LV), the density coefficient 2.4 has been used by default. The default value for load size is based on results of productivity study.

The model calculates the hourly cost (productive, engine and proposed working hours) and the unit price for each phase of the harvesting process.

Sensitivity analysis includes a range of certain input data, from minimum to maximum value obtained during the studies, national statistics or the data provided by the contractors, for instance fuel consumption for the same type of machine, average forwarding or road transport distance, or applicable range of dimensions of extracted trees (usually obtained from time studies). These values are used to determine range of costs depending from value of the parameter. The model is validated against actual harvesting contracts in state forests and hourly costs of rental machines.

RESULTS AND DISCUSSION

Harvesting costs consist of forwarding, logging and road transport of roundwood, as well as the costs of biofuel extraction where applicable. Different models are used for prime cost calculation by researchers and enterprises (FAO, 1992; Väätäinen, et al., 2006; Ackerman et al., 2014), but there is still unfulfilled demand in a model giving detailed view of the prime cost of different forest operations, integrating productivity and costing parameters in dynamic calculation system.

In different cost calculation models various factors affecting costs are taken into account (FAO, 1992; Väätäinen et al., 2006; Spinelli et al., 2009; Harrill & Han, 2012; Ackerman et al., 2014). Logging, forwarding and roundwood delivery costs are heavily affected by dimensions of the average extracted tree, which needs to be represented in sensitivity analysis to see threshold values in expected range of the work conditions. The average productivity of logging, forwarding and road transport (the last 2 values are determined by load volume) are calculated for each diameter class and used in the calculation.

The cost calculation model allows to vary the factors affecting prime costs of several machines, choosing the type of preparation and delivery of roundwood and harvesting residues, planning work hours of forest machines, changing working conditions and forest machines (Fig. 1).

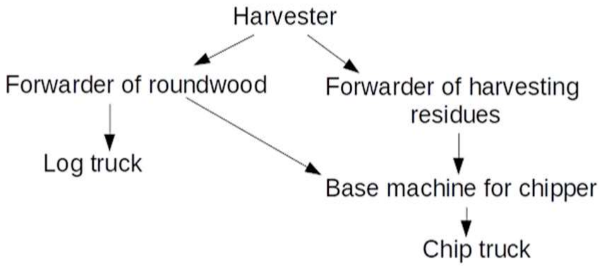

Figure 1. Modeling of harvesting system in forest operations.

Most of the cost calculation models predict calculate the cost of each separate forest machine, which do not represent how interaction of the machines and changing logging conditions can affect the cost of production and how to achieve higher economic efficiency (Ackerman et al., 2014). The following example (Table 3) shows how costs are analyzed in the proposed model.

Table 3. Example of output of cost calculation

Calculation items	Harvester	Forwarder of round wood	Log truck	Forwarder of harvesting residues	Chipper	Chip truck
Summary of costs, € per year						
Investment costs	51,725	39,058	15,206	41,246	71,194	15,212
Labour costs	62,637	62,637	72,692	62,637	60,765	72,692
Operational costs	103,896	53,056	31,207	51,102	172,673	39,150
Profit margin	10,913	7,738	5,955	7,749	15,232	6,353
Total	229,171	162,488	125,060	162,734	319,864	133,406
Productivity						
Roundwood with bark, m^3 E_{15} h^{-1}	6.7	10.0	10.6	-	-	-
Biofuel, LV m^3 E_{15} h^{-1}	-	-	-	37.5	96.5	23.9
Amount of roundwood and biofuel produced per each unit of machinery per year						
Total roundwood, m^3 per year	19,144	26,778	14,658	108,793	90,318	35,753
Logs, m^3 under bark	15,955	24,125	13,205	-	-	-
Biofuel (stem residues), m^3 per year	1,434	-	-	-	-	-
Biofuel (logging residues), m^3 per year	-	-	-	108,793	-	-
Bark and other residues, m^3 per year	1,755	2,654	1,453	-	-	-
Biofuel (wood chips), LV m^3 per year	3,443	-	-	261,103	216,762	85,807
Output						
Logs under bark, € per m^3	14.4	6.7	9.5			
Biofuel, € per LV m^3				0.6	1.5	1.6

Basic model version can be used to calculate if it is cheaper to deliver forest biofuel as logs or chips (Table 3); however, it can be easily adapted to different comparisons including system analysis.

According to the sensitivity analysis implemented in the model, the diameter of the average extracted tree significantly affects productivity. Similar or simplified approach can be used to determine, how the forwarding and road transport distance affects costs of production and to find threshold values for these parameters. Built in spreadsheet linear optimization functions can be used to determine the threshold values. Similar conclusions are also available in other studies (Väätäinen et al., 2006; Harrill & Han, 2012).

The model can be used to identify the factors affecting total harvesting and delivery cost under theoretical or real life conditions based assumptions (Figs 1 and 2).

Any other parameter considered in the cost calculation can be added to the sensitivity analysis. Where applicable, the sensitivity analysis should be combined with productivity models or equations. For example, change of dimensions of extracted trees should reflect in productivity of harvester, as well as on load size in off-road and road transport, reflecting in productivity of forwarder and log truck.

Sensitivity analysis of forwarder driving distance (Fig. 2) shows that increase of forwarding distance by 150 m in the conditions used for verification of the model increases the total production cost by 0.5 EUR per m^3. Fuel consumption can also be differentiated in the model, for instance, different values of fuel consumption can be applied for driving loaded and empty, as well as for loading and unloading operations.

Sensitivity analysis of utilization rate (Fig. 3.) demonstrates that increase of the utilization of harvester significantly reduces total production cost. Similar effect is observed for all machines due to increase of indirect cost per working hour.

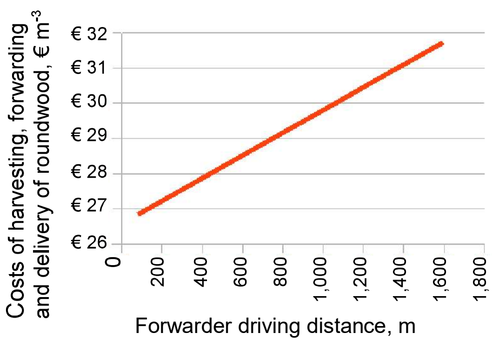

Figure 2. Sensitivity analysis of forwarder driving distance.

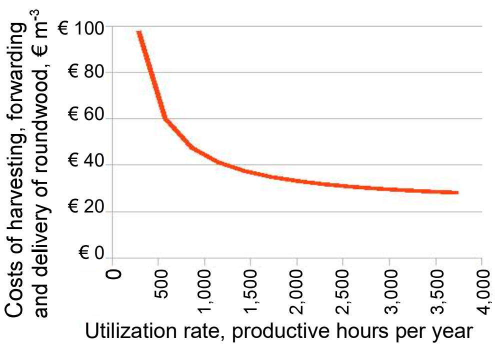

Figure 3. Sensitivity analysis of the utilization rate.

Comparison of the calculation results with actual harvesting costs in 2017 provided by the Joint stock Company 'Latvia state forests' and Central statistical bureau approves that the modeled values are within the uncertainty range of available statistical data; however there is still considerable potential for underestimation of harvesting costs by utilization of the study data due to overestimation of the utilization rate of forest machines. This parameter was estimated using expert judgments in contrast to other parameters, where dealers' centers or contractors' information is available. Therefore, the calculation was tuned to conform to the real harvesting prices by changing the utilization rate. Other parameter significantly affecting cost of production is salary rate; some companies are paying fixed monthly salaries, some are paying per produced unit, some are combining these 2 methods. As a result, provided monthly or hourly salary rates differ a lot between companies, in spite the average annual income has no tendency of such a big variation. The model uses average hourly rate assuming full-time employment as a basic assumption, which can lead to overestimation of personnel costs in case of combined or per piecework payment scheme.

CONCLUSIONS

The elaborated model is simple in use, easily extensible with additional parameters, machines and equipment. It can be used in practice, at a company level to analyze and to predict machine costs, as well as in research for system and sensitivity analysis.

One of the largest benefits of the model is using of engine hour as a reference time unit providing opportunity to use machine service data in cost calculations without adaptation of the applied data.

The model contains internal system of quality assurance, like calculation of the net income of operators and a company, and the hourly cost of machine, which can be validated against the service data.

The model is supplied with the default input data, which are already validated in Latvia and can be easily adapted to other conditions providing at the same time opportunity to avoid logical mistakes in data entering, like use of non-realistic values for consumption lubricants or fuel.

The model allows to get an overview of the cost of the machine system in dynamic conditions, which, accordingly, allows to choose the most efficient combination of machines, threshold values for certain operations, like off-road transport distance, and stand parameters, like minimum dimensions of trees.

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