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A cost model for forest machine operation
in wood cutting and extraction

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1. Introduction

The evaluation of a wood cutting and extraction system is primarily concerned with the system selection and assessing of the environmental impact of the mechanized operations. The machine options for sensitive sites should satisfy the economic feasibility, have a social acceptance, and deal with environmentally sound equipment employed. Based on the forest machine operability in given site conditions, the machine operating costs and timber harvesting productivity will be the two main factors in the appropriate selection of the machines. In addition, the environment-oriented method should give emphasis on optimizing the total wood cutting and extraction system. In this report, the most important parameters are identified and discussed. An evaluation method for the potential environmental risk is presented in a practical way. Furthermore, a contingent function for estimating the environmental costs derived from the forest machine operations has been defined in a general sense.

Modeling of the harvesting machine cost calculation and the analysis should take into consideration the effectiveness, the flexibility, and the ease to use for the end-user. In this report, a program application of the cost model has been developed on the basis of the window-based programming procedures. The user-friendly interface design of the application program facilitates the data input, the output of results, and the communications among the routines. The output from the cost model will be used for aiding the machine selection and operational decisions in timber harvesting from sensitive sites.

2. The methodology for modeling the harvesting machine costs

The basic principle when analyzing the machine operation and its machine system is to compute the operational costs based on the labour and machinery used. The machine costs involve the costs of running a machine over its expected useful life. The main concern in the machine costs is based on the calculated fixed and variable costs. The fixed costs are incurred through ownership of the machine and are independent from the annual working time. The variable costs are incurred when the machine is being used and depend on it. On the other hand, the forest machines operated in forest always may cause environmental problems, such as damage to the remaining stand in a thinning operation, soil compaction or soil disturbance. The environmental impact to the forest should be limited. In other words, the environment impact should be transferred into the machine operational costs as an extra cost. Thus, the environmental costs should be included in the total machine operating costs. The general form of the machine costs can be defined, as follows:

\[ C = MC + RC \]

where: \( C \) = Total cost for a period
MC = Conventional cost for any time period, including fixed and variable costs
RC = Environmental risk costs

The conventional costs can always be indicated by a machine utilization rate. It breaks down the costs for a period into cost units. In the procedure of cost calculation, the fixed costs of the machine are aggregated per shift hours. The variable costs imposed by the actual work are allocated on those hours of the shift when the machine actually performs a work. The scheme of the cost calculation model includes four groups of items, as shown below (Mikkonen & Lan, 1999):

1) Working time parameters
   - Working shift
   - Scheduled hours
   - Move of the machine
   - Downtime, repair
   - Machine utilization rate and its economic life time

2) Machine and its add-on equipment price:
   - Total price
   - Taxes, interest and insurance
   - Finance, interest payment, and principal payments, etc.

3) Salvage value and the depreciation scheme
   - Depreciation scheme and its value
   - Salvage percentage and its value

4) Consumption items
   - Fluid consumption
   - Consumption of work

The environment cost involves the valuation of the environmental impact and transformation. In general, when estimating the tree damage in a thinning operation one may convert it to a lost cost. However, it is very difficult to quantify by an analysis the environmental costs. More details on it will be discussed in a later section.

The productivity in harvesting timber is a crucial factor when identifying the machine performance in real circumstances. The higher is the productivity, the less costs the machine is causing. Selection of an individual machine or a machine system should be based on a procedure of cost efficiency analysis. In modeling the costs and timber production, a model development is based on the cut-to-length system (harvester and forwarder) specifications. The production functions for estimating the work productivity of the cut-to-length system has been well justified by Rummukainen et al. (1995).

The application programming will emphasize the user-friendly interface design and the ease use of the program. A window-based program is developed for the end-user by using the Delphi development tool.
3. Timber harvesting operation and environmental impacts

Machine operations in forest may cause soil compaction, site disturbance or damage to remaining trees. The most extensive soil compaction is produced by the machine traffic during the off-road transport. The extent of compaction depends on the type of machine, its load capacity, as well as on terrain conditions, e.g. the nature and state of soil. Site disturbance is a result from the interaction between the machine and the forest floor. The total cross- sectional disturbance indicates the impact and extent of rut formation into the ground. Rut formation largely depends upon the structural parameters of the particular machine. Damage to forest stand may be serious in thinning operations. Some of the damage to the remaining trees is caused by timber processing with a long-reach boom. Besides the skidding road spacing used and the skill of the machine operator, the type and dimensions of the machine are determining factors affecting the level of damage in stands.

Assessing of the forest machine operation and estimating of the environmental risk are crucial tasks in selecting a wood cutting and extraction system. The extent of the environmental impacts caused by the mechanized operations is strongly dependent on the multiple parameters such as harvesting methods, machine structural properties, and operating factors. The most important parameters to be considered might involve the following ones:

1) Slope of terrain. The slope is essentially affecting the impact of the machine operation. Machines operated on steep slopes cause more damage to the forest floor than those used on level ground. On the other hand, the slope-climbing capacity of the machine may also reflect the extent of the environmental risk. It influences the operability of an individual machine and machine system.

2) Soil conditions. The soil characteristics determine the trafficability of the site and the risk to damage the forest floor. In addition, the ability of the soil to resist the effects of machine traffic is also an important factor.

3) Harvesting methods and logging pattern. Different types of harvesting methods cause various damage to the forest floor and stands. Logging pattern determines the damage to stands, too.

4) Machine size. In general, forest machines can be divided into three groups: small, middle-sized, and large. The machine size determines the ground pressure. The dimensions of the machine in relation to the forwarding track spacing, the ground clearance and maneuverability between the trees, directly affect the eventual consequences to damage the stand in a thinning operation.

5) Machine type and operational mode. Different types of machines are used to form a harvesting method. The machine type also determines its operational mode. For instance, harvesting and forwarding often cause less damage to the trees than the tree-length skidding. Direct dragging and winching are often the most dangerous for the standing trees. Skidding and feller-bunching will also disturb large areas when used.
6) Ground pressure and tyre types. The ground pressure of a machine is the basic cause for soil compaction. The extensive disturbance indicated by the rut depth heavily depends on the type and size of tyres. Wider tyres or tracks contribute efficiently to reducing the soil damage and rutting.
<table>
<thead>
<tr>
<th>Scale level</th>
<th>Terrain slope</th>
<th>Soil condition</th>
<th>Harvesting method</th>
<th>Machine size</th>
<th>Operation mode</th>
<th>Ground pressure (kPa)</th>
<th>Tree type or track</th>
<th>Ergonomic features</th>
<th>Operation skill</th>
<th>Harvesting pattern</th>
<th>Machine cost-efficiency</th>
<th>Machine productivity</th>
<th>Machine slope capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 8</td>
<td>Good</td>
<td>CTL</td>
<td>S</td>
<td>Harvesting</td>
<td>&lt; 80</td>
<td>narrow</td>
<td>good</td>
<td>good</td>
<td>First thinning</td>
<td>good</td>
<td>good</td>
<td>suitable</td>
</tr>
<tr>
<td>2</td>
<td>9 - 15</td>
<td>Moderate</td>
<td>TL</td>
<td>M</td>
<td>Forwarding</td>
<td>80 - 120</td>
<td>Normal</td>
<td>acceptable</td>
<td>satisfactory</td>
<td>Other thinning</td>
<td>satisfactory</td>
<td>satisfactory</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>3</td>
<td>16 - 25</td>
<td>Poor</td>
<td>WT</td>
<td>L</td>
<td>Fell-bunching</td>
<td>121 - 140</td>
<td>Wide</td>
<td>Poor</td>
<td>Poor</td>
<td>Clear cutting</td>
<td>high</td>
<td>low</td>
<td>Difficult</td>
</tr>
<tr>
<td>4</td>
<td>26 - 35</td>
<td>Very poor</td>
<td>-</td>
<td>-</td>
<td>Skidding</td>
<td>&gt; 140</td>
<td>Tracks</td>
<td>Very poor</td>
<td>Very poor</td>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Weighting significance \( \sum_{i=1}^{n} x \) x x x x x x x x x x x x x x x x

Weighting points x x x x x x x x x x x x x x x x x x x

Risk level 1 - 4 < 0.30 \( \geq 0.30 \) & \( \leq 0.60 \) > 0.60 & \( \leq 0.80 \) > 0.80

Total \( \frac{1}{n} \sum \)

Note: CTL - Cut-to-length, TL - Tree length, WT - Whole tree; S - Small, M - Middle, L - Large; x - applied or calculated.
7) Ergonomic features of the machine and the operator. Operator's skill strongly affects the extent of damage to forest floor and remaining trees during the machine operation. Ergonomic features of the machine also have an effect to operator's performance, which some way should be included into the environmental risk assessment procedures.

Table 1 shows the environmental risk assessment matrix for a forest machine operation. Into this table, the most important environmental parameters are extracted from the machine structural parameters and timber harvesting environmental factors. The list must be considered in assessing the environmental impact of a forest operation. The matrix is used as a starting point to help the making of quantitative estimates on potential environmental risks. It is important to normalize these quantities and to introduce uniformity of the measurement, which result in unitless or dimensionless measures. The basics of the risk assessment could be defined as following steps:

1) Measurement of the risk value for each parameter can be defined as an indicator with zero and 1 being the best/worst possible value respectively.
2) For a specific machine, the risk value for each parameter can be assigned a value arranged between zero and 1, based on the machine specifications and real circumstances of the forest operation.
3) Each factor can also be given a weight of zero to 1 that reflects their relative contribution to the estimate of a potential environmental risk as a whole.
4) That total value can be used as an integrated environmental risk assessment for a specified machine to be employed.
5) In practical use, the risk value can be divided into four levels, as recommended in the Table 1. The risk level in general indicates the extent of the environmental impact of a timber harvesting operation to the forest site.

The matrix is designed to provide a record to support the appropriate selection of the timber harvesting equipment. On the other hand, the risk level could be introduced into the valuation of the potential operational damage to the remaining trees and forest floor etc. in terms of an environmental cost. No doubt, it is difficult in the reality to carry out the quantitative processes when identifying the environmental costs derived from forest operations. In general, the many parameters involved in measuring the environmental costs make it difficult to obtain a satisfactory answer in terms of traditional analysis methods, for instance the cost-efficiency and cost-benefit analyses. Thus, a contingent valuation method could be used to estimate the environmental cost derived from the impact to a forest operation (Lan, 2001):

\[ RC = a \cdot C_m \cdot \frac{AR}{SR}, \]

where
- \( RC \) = environmental cost for a specific machine in a given condition,
- \( a \) = a policy coefficient, relating to the social-economic and environmental issues,
- \( C_m \) = machine cost as hourly rate, calculated by the cost model,
- \( AR \) = actual environmental risk level to a specific machine in a given condition,
- \( SR \) = standard environmental risk level.
In the formula, $\frac{AR}{SR}$ expresses a relative concept in the valuation the environmental risk. It can be transformed into a proportion of the cost-benefit measurement. A standard environmental risk level, $SR$, could be defined as a risk level accepted in a general sense of the forest machine performance. The policy coefficient $a$, being a constant, could be expressed as a percentage of machine’s operational costs based on the environmental policy or other social considerations, which to a large extent is related to the decision-making process of the environmental policy, in general.

The environmental cost estimated by a contingent function above could provide a basis in terms of the environment-oriented procedure in forest machine selection. The valuation of the environmental impacts makes it clear that the damage to stands and forest site must be controlled to some extent. In the following sections, the design of the program for the cost calculation is discussed and further developed for a real use. It should be mentioned that at this stage the program development does not include the part of environmental costs because of lack of data. In the future development, the program can easily be updated and extended in a more widespread forest machine cost calculation.

4. Description of the programming of the cost model

A harvesting machine cost calculation model has been developed for the user by using the Delphi window-based development tool. In addition to the machine cost calculation, the model for estimating the timber harvesting productivity of a cut-to-length system is also included in the program. The productivity of either a harvester or a forwarder can be calculated by the built-in production functions. The model is used to generate the actual data for the appropriate selection of wood cutting and extraction system. The cost calculation could be carried out in two different ways:

1) Cost calculation for a single machine.
2) For a machine combination included in a production system.

**Interface design for the main window**

When starting the program the main window will be opened. The main window in a cost calculation program is shown in Figure 1.
In the main window, the user should specify the two groups of parameters, including the working time assumption and basic parameters for the cost calculation. These are divided into several groups, as follows:

1) Interest formula
   - Short term
   - Long term, or
   - Annually

2) Depreciation scheme
   - Salvage
   - Decreasing-in-value

3) Residual value scheme
   - Even sum yearly
   - Degressive
   - Progressive

4) Monetary
   - Euro
   - USD
   - FIM
   - DM
   - SEK, or
   - Other

5) Working time assumption
- Months per year
- Days per month
- Hours per day
- Machine utilization, %
- Machine life, years
- Moving time, %
- Percentage for depreciation, %

Once the basic assumption parameters are selected or the input given, by using the pull-down menu one can open the data input window for the cost calculation. The menu includes:

- "Input data": the input data for a single machine
- "System": the input data for the machines in a production system

In fact, the cost calculation model is functioning for the different types of machines, such as harvester, forwarder, feller-buncher, skidder and so on. In this interface design, the speed button "Input data" and "System" is functioning similarly to the pull-menu.

**Data structure and interface design for the data input**

A click in the "Input data" in the main window will open a window for the input data. Its interface is shown as Figure 2. The pull-down menu shows the various functions of the cost calculation and analysis. These include functions such as cost calculation procedure, cost analysis, estimating of the productivity of a specified machine, a cost report, and a cost data file management. There are:

1) File: to open existing files, to save new data to a file etc.
2) Cost analysis: a machine cost analysis function included
3) Productivity: a module for estimating the machine productivity
4) Reports: a cost report for the user
Interface has been designed as a series of data to be fed in in the cost calculation model. It consists of four groups of cost factors as follows:

1) Machine price
   - Machine price
   - Its appliance
   - Interest rate (%)
   - Residual value or value used in decrease-in-value calculation

2) Consumption figures
   - Social security cost (%)
   - Contractor risk cost (%)
   - Fuel consumption per hour: including fuels, lubricants, and hydraulic oils
   - Per diem cost items: including as follows,
     -- Operator driving, units per year
     -- Diem per year
     -- Times of trips to home per year
     -- Contractor driving, units per year

3) Wages and fringe benefits
   - Wages: hourly rate, or accord rate
- Extras per hour: for shift work, for cold weather, or for repair work
- Fringe benefits: costs of a car (per unit of distance), per diem, or cost of the home trips

4) Cost figures
- Overhead costs, yearly
- Repair and service, yearly
- Special items, yearly
- Insurance per year: including fire, traffic, etc. damage
- Fuel and lubricants, price per unit: including fuel, lubricant, and hydraulic oil

The input data by the user is based on the specified machine models. Once all data are ready, then click the "Calculate" button and the results of the total costs per year and hourly costs will be displayed in the box "Cost result". The cost factors and results can be saved to a specified file. The user can also report the machine costs and print them out. A single click of the "Report" button will open a window dialog box as shown in Figure 3. In this window, the user can select an item in radio-button box and print its result out. The report is formatted to include both the original data on various items and the calculated machine costs.

![Figure 3. Dialog box for the cost report](image)

**Analyses of the cost items**

In the cost calculation model, there are as many as 36 cost factors to be included. In general, each factor can be assigned to different values with a reasonable range. The cost analysis will indicate the changes of the machine costs in relation to a specified cost item within the bounds. In this model, cost analysis procedures are shown as in Figure 4. There are two kinds of analysis procedure, one way and two ways in different cases. These can be selected by a simple click in a box "Way of analysis".

1) The one-way method. It concerns only to activate the main cost item box. One cost variable can be selected; and the user should define the "Lower bound" and the "Upper bound" of the selected variable, and the points of the analysis.
2) The two-way method. It involves the main cost items and items related to it. Also the lower and upper bounds can be defined.

Once the cost item is selected, a click at the "OK" button will display the results in two different ways. The analyzed results can be shown in a table and in graphical form. The user can easily change the type of the graphical display by clicking the corresponding button as shown in the interface design.

**Estimation of the productivity for a specific machine**

Estimating of the productivity for a specific machine under real environment is based on the built-in production functions concerning each type of machine and model. The productivity of the machine provides the basis for machine selection in a production system. It is generally used as a criteria in forming the timber cutting and extraction system together with the operating costs. The window for estimating the machine productivity is shown in Figure 5. It should be noted that the built-in production functions are used to estimate the productivity of harvesters or forwarders only. The productivity is calculated in accordance with the timber harvesting parameters and operational conditions. In the interface design, the data types are grouped in different "boxes", as shown below:
1) Operation type
2) Machine type: harvester or forwarder
3) Machine size: small, middle-sized, and large for harvesters
4) Forwarder size: 4 t, 6 t, 8 t, 10 t, and 12 t
5) Species: softwood (%), or hardwood (%)
6) Timber assortment: sawlogs, 5-meter pulp, or 3-meter pulpwood
7) Production parameters: stem volume (dm$^3$), timber density (m$^3$/100m), off-road transport distance (m), and
8) Terrain class (in Finland): class 1, class 2, and class 3

Figure 5. Interface design for estimating the machine productivity

Once the data are filled in and the other related factors selected, a simple click of the "Calculate" button will provide a simple result for the specified machine productivity. Estimating of the productivity for each type of machine and its model is based on the corresponding production function under given conditions. The productivity results can be saved as a file for reference use.

In addition, in the interface design of this model, it also provides an analysis procedure for the machine productivity with various graphical display methods. For instance, the analysis results may show the correlation between the productivity in effective time and the stem volume in case of operating a harvester. In the case of a forwarder, the analysis will show the correlation between the productivity in effective time and the off-road transport distance.
5. Discussion and conclusions

The cost model utilizes basic cost calculation principles, which can be applied to various types of forest machines and to different kind of machine models. Estimating of the productivity under given conditions is limited to a harvester and forwarder production system because of lack of well-justified production functions for the other machine types. The model program for real use has been developed with the Delphi window-based development tool. It can be run on a PC platform with a Windows operating system. The graphical interface of the program is designed to be as user-friendly as possible. It really is easy to use.

At the present stage, the model cost program does not include a part to estimate the environmental costs derived from the impact of forest machine operations. Some gained research results are just from a case study, which can not be used for general purpose. Through a contingent method they might be used to estimate the environmental costs for a specific machine, to the evaluation of the environmental risk level and to identify other related factors when becoming critical. From the point of view of the program design, once the methods to estimate the environmental costs are identified, the program is easily extended and further developed.

6. References