FORMEC 2010
Forest Engineering: Meeting the Needs of the Society and the Environment
July 11 – 14, 2010, Padova – Italy

DEVELOPMENT OF A MULTI-CRITERIA SPATIAL EVALUATION MODEL FOR DECISION SUPPORT IN TIMBER HARVESTING PLANNING

Martin Kühmaier

Institute of Forest Engineering
Department of Forest and Soil Sciences
University of Natural Resources and Applied Life Sciences
Peter Jordan Strasse 82/3
A-1190 Vienna, Austria
e-mail: martin.kuehmaier@boku.ac.at

Keywords: timber harvesting planning, decision support, evaluation model, utility analysis

Abstract: *Strategic and tactical decisions in timber harvesting planning have long-term consequences on the further development of forests. Harvesting activities are often based on intuition and the consequences of these actions cannot be determined exactly. To support the decision making process in timber harvesting an evaluation model was designed, which compares harvesting systems and selects the best suitable system in consideration of stakeholder interests and environmental conditions.*

The developed model is made up of four stages. First the investigation area is defined. In the next step a technological evaluation of harvesting systems was implemented, where the capability of harvesting systems was determined by comparing their specification with location factors. Only concordant systems have been included into the third stage, the utility analysis. The analysis calculates the best suitable system by considering evaluation criteria, transforming them into comparable values and ranking these values. The last stage of the model analyses different scenarios and estimates the consequences of the harvesting program. To involve spatial dimension the evaluation process was implemented in GIS. Main processes have been automated in ArcGIS by using the ModelBuilder extension.

The model has been demonstrated for different scenarios in a 1,100 ha sized forest enterprise in steep terrain in the South of Lower Austria. One scenario analyses the improvement of the forest opening by implementing a new forest road. In the opened area the productivity could be tripled, emissions and stand damage were sinking but the soil pressure increased dramatically. The contribution margin rose from 40 to 56 €/m³. Another scenario determined the consequences of the implementation of new harvesting technologies. The main effects of the introduction of "cable forwarder" technology are the quadruplication of soil pressure, a reduction of stand damage by 2 percent points and a raise of contribution margin from 40 to 46 €/m³.

1. Introduction

Timber harvesting is one of the main objectives in forest management. It has positive effects in raising the contribution margin of the forest enterprise, but also long-term ecological and social impacts. Thus indicates an important key-role for choosing an adequate timber harvesting system.

Decisions in timber harvesting planning are mostly made on the short term. They are based on experience and intuition and do not consider a long-term and sustainable strategy of resource management. As a result of these antiquated background it is difficult to react in case of changes, e. g. in felling volume or technology. Admittedly, the increase in production costs and the development of new technologies presupposes a continuous review of the used systems and an adaption of deadlocked structures. To estimate the effects of these changes, a decision support would be helpful, especially for important strategic and tactical goals. The knowledge of the impacts of using different harvesting systems plays an important role such as for estimating costs and the need of machinery and work force.

Until now the economic efficiency has been indicated as the most important or almost only criterion for selecting harvesting systems. Ecological and social criteria haven't been considered so far, as it can be seen in comparable studies (Lüthy 1998, Mallinger, 2002). This non-consideration may impose such negative side-effects and high risks so that the economic advantage will be revoked immediately. Harvesting systems with a high value in contribution margin could have negative impacts e.g. on the soil, the remaining stand, climate, employment and working safety. Therefore, a well-grounded analysis of harvesting systems should take stand and terrain data as well as ecological, economic and social data into account. Since this decision problem consists of several criteria and bears so many trade-offs, a satisfactory solution could hardly be found without using technical and mathematical tools. For that reason a multi-criteria, computer-aided DSS could be a good approach (Lexer et al. 2005).

Harvesting operations will be implemented on a spatial level. Equipment and work force have to be carried to the utilization area and the harvested timber will be transported from the stand to the saw mill. The accessibility of the forest area depends on existing infrastructure and the relief of the terrain. These spatial information and the topological interactions could easily be considered with GIS technology. By the use of IT-systems data preparation, management, analyses and information exchange would be easier to handle.

In recent years some studies have been published to estimate different harvesting systems on the base of forest districts or compartments (Lüthy 1998, Meyer et al. 2001, Yoshioka & Sakai 2005). In Austria a technological evaluation, but without a comprehensive analysis of the different systems has been prepared by Mallinger (2002). Nevertheless, none of these studies took ecological or social criteria into account, which also indicates the impossibility of making conclusions to the impacts of the systems.

The aim of this study is to develop a multi-criteria spatial evaluation model for decision support in timber harvesting planning on a mid- to long-term level. To support the evaluation, a utility analysis will be used. Within this model environment conditions will be taken into account by implementing terrain, stand and machinery data. The preferences of the user will also be considered via weighting of different evaluation criteria. The evaluation model estimates the best suitable system for the potential harvesting area(s). Further results will include the consequences of the harvesting program for different scenarios.

2. Material and methods

The evaluation process is made up of four stages. First the investigation area has to be defined. In the next step a technological evaluation of harvesting systems was implemented, where the capability of harvesting systems was determined by comparing their specification data with location factors. Only concordant systems have been included into the third stage, the utility analysis. The analysis calculates the best suitable system by considering evaluation criteria, transforming them into comparable values, and aggregating and ranking these values. The last stage of the model analyses the consequences of the harvesting program for different scenarios.

The different stages of the model (Figure 1) will be described in more detail on the next pages. To involve spatial dimension the evaluation process was implemented in GIS. Main processes have been automated in ArcGIS by using the ModelBuilder extension.

The functionality of the model will be demonstrated by means of concrete application examples. Therefore different treatment alternatives will be compared and their impacts on the used criteria estimated. The quality of the model will be checked via sensitivity analysis. For this reason the weighting of the criteria could be changed and the indicated impacts analysed. All these scenarios will be demonstrated for a selected forest enterprise in the South of Lower Austria.

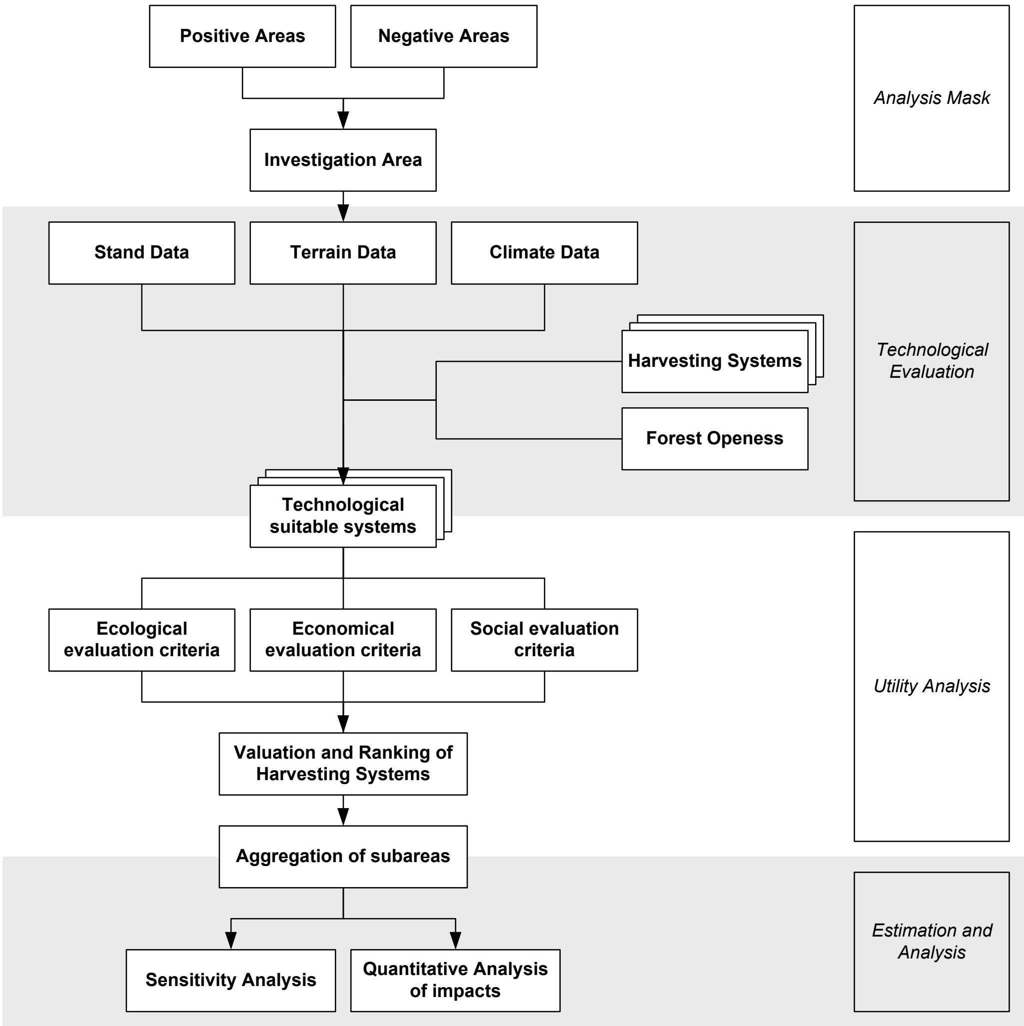

Figure 1: Decision Support Model for the evaluation of harvesting systems

2.1 Analysis mask

The analysis mask will be determined via multiple steps. After defining the investigation area desirable zones (e. g. forests) will be intersected with non-desirable (protected or prohibited areas). These data layers will be combined in GIS.

For demonstration of the model a 1,100 ha forest area in steep terrain has been chosen. The sea level is about 550 – 1,100 m, the average precipitation about 1,300 mm per year. The forest road density reaches 34.8 running meters per ha. The main tree species are spruce (60 %) and pine (25 %).

2.2 Technological evaluation

10 different harvesting systems have been taken into account for the technological evaluation. They differ in four grades of mechanization and three working methods. The evaluation process includes also hardly used harvesting systems, e. g. manually skidding, because for small areas and a little amount of timber they are still in use.

Table 1: Harvesting systems and equipment subject to stand and terrain data

	Harvesting System Technological Specification	Used Equipment and Machinery
1	**Motor-Manually, Cut-to-length method** Slope 30 - 60 %, Terrain accessible	Chain saw & Manually skidding
2	**Partly mechanised, Cut-to-length method** Slope < 30%, Terrain accessible	Chain saw & Forwarder
3	**Partly mechanised, Cut-to-length method** Slope < 60%, Terrain accessible	Chain saw & Cable Forwarder
4	**Partly mechanised, Tree-length method** Slope < 30%, Terrain accessible	Chain saw & Skidder
5	**Fully mechanised, Cut-to-length method (< 30 %)** Slope < 30%, Terrain accessible, DBH max. 40 cm	Wheeled Harvester & Forwarder
6	**Fully mechanised, Cut-to-length method (< 60 %)** Slope < 60%, Skidding distance < 800 m, Terrain accessible, DBH max. 40 cm	Tracked Harvester & Cable Yarder
7	**Fully mechanised, Cut-to-length method (< 60 %)** Slope < 60%, Terrain accessible, DBH max. 40 cm	Tracked Harvester & Cable Forwarder
8	**Partly mechanised, Cut-to-length method** Slope < 100%, Skidding distance < 800 m	Chain saw & Cable Yarder
9	**Highly mechanised, Tree-length method** Slope < 100%, Skidding distance < 800 m	Chain saw & Cable Yarder & Processor
10	**Partly mechanised, Tree-length method**	Chain saw & Helicopter & Processor

For the technological evaluation four criteria have been chosen. They act as specification data for the applicability of the selected harvesting system under given circumstances. The slope, expressed in %, is a limiting factor for wheeled (30 %) and tracked (60 %) machines. The given limits are average values; they can vary depending on relief and bearing capacity of the terrain. Another specification criterion is the skidding distance. It is a limiting factor for cable-supported machines, e. g. cable yarders (800 m) and skidders (200 m). The limiting DBH for harvester and processor depends on the type of machine. A strongly varying morphology is a restricting factor for ground-based systems as a result of reduced trafficability.

By combining these input data, for every harvesting system a “technology layer” will be calculated. To carry the machines to the utilization area the terrain has to be accessible. If there are generally utilisable zones surrounded by non-usable these areas will be shifted to the next possible technology layer. Furthermore climate criteria will be considered, which are restricting harvesting periods because of a high snow cover or advantageous factors for the trafficability caused by frozen soil. The technology layers act as input data for the utility analysis.

2.3 Utility analysis

For the comparison of technologically suitable systems a utility function based on preference models was used. In a case of multi-attribute utility function, it is assumed that there are *m* criteria, and a unidimensional utility function for each of these criteria. The task is now to aggregate these utility functions to describe the overall utility of the alternatives. This aggregation is done by weighting of the criteria in the utility function with respect to their importance. The relations between the weights of different criteria describe the tradeoffs between the criteria (Kangas et al. 2008). The calculated overall utilities give the information of the performance of the alternative (harvesting systems). The best suitable alternative is that one with the highest overall utility.

The most applied multi-attribute utility function is the linear additive utility function

$$U_i = \sum_{j=1} c_{ij} \quad (1)$$

where U_i describes the overall utility of alternative i (or priority of alternative i) and c_{ij} is the performance of alternative i with respect to criterion j and a_j is the importance weight of criterion j. In this equation, it is assumed that the criteria values c_{ij} are already in utility scale or are scaled with a value function. Typically it is required that

$$\sum_{j=1}^{m} a_j = 1 \quad (2)$$

otherwise the utility could always be increased by increasing the weights. The tradeoffs between criterion k and k' can be calculated from the ratio of the weights $a_k/a_{k'}$. In general, the marginal rate of substitutions between criteria k and k' can be calculated as a ratio of partial derivatives of the utility function as

$$\lambda = \frac{U'_k}{U'_{k'}} = \frac{a_k}{a_{k'}} \quad (3)$$

This means that the decision maker is willing to give up λ units of criterion k' in order to increase the value of criterion k by one (Kangas et al. 2008).

Evaluation criteria should be independent from each other, i.e. that the achievement of one goal does not influence the performance of another goal. Indicators are variables, which indicate the status of criteria. For the evaluation model ecological, economic and social criteria have been chosen. Seven criteria (bold) and indicators (italic) are represented in Figure 2.

The criteria values have been scaled via value functions. There exist several methods for estimating value functions. In this study the natural scale values have been scaled with score range procedure

$$v_i = c_i - \mathrm{nin}(c))/(\max(c) - \mathrm{nin}(c)) \quad (4)$$

The best alternative is assumed to have a value one, and the worst the value zero. In this case, if min (c) > 0, the alternatives do not follow a ratio scale, but an interval scale. Interval scale can be interpreted as local scale, the length of which depends on specific planning situation (Kainulainen et al. 2007). Figure 3 shows, as an example, the value function for the value added in €/m³. This linear function has a value of zero below -20 €/m³ and a value of one above 100 €/m³.

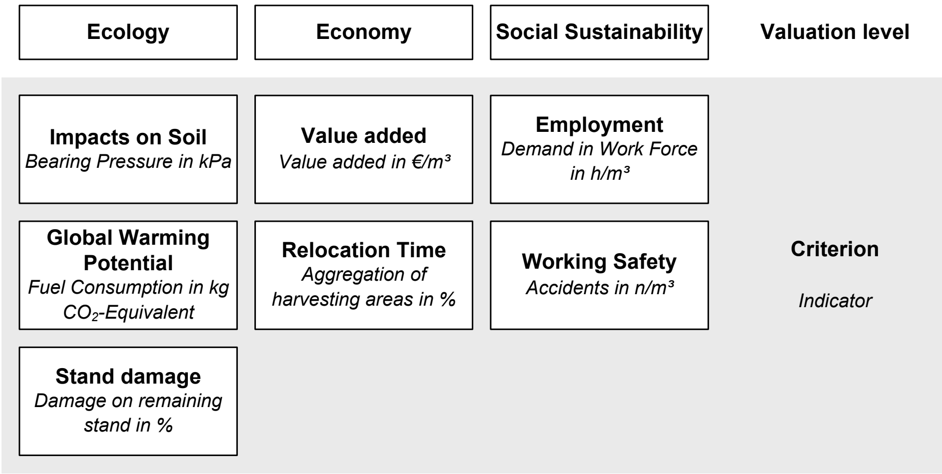

Figure 2: Valuation levels, criteria and indicators

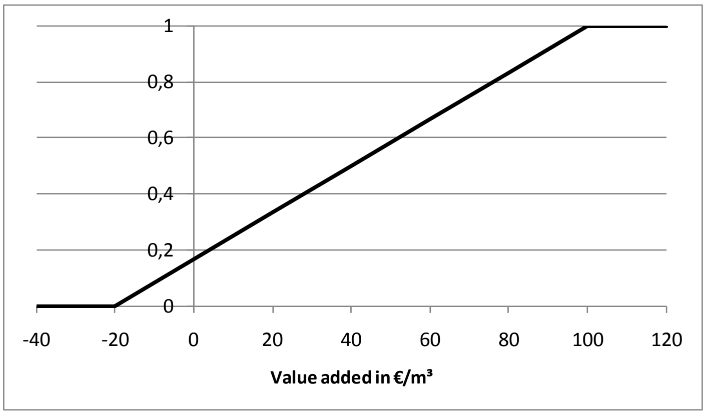

Figure 3: Value function for value added

A large number of methods is available for estimating the weights in the utility function. Generally, they can be divided to two main categories: direct and indirect methods. In direct methods, which have been used for this study, the estimation is based on direct questions concerning the importance of criteria in the decision situation at hand. SMART and AHP are popular direct methods (von Winterfeldt and Edwards 1986, Saaty 1977). The weights of the criteria for the model demonstration are represented in Table 2.

Table 2: Criteria weighting

Criterion	Impacts on Soil	Global Warming Potential	Stand Damage	Value added	Relocation Time	Employ-ment	Working Safety
Weight	5 %	10 %	15 %	35 %	5 %	10 %	20 %

The overall utility for each alternative (harvesting system) and for every subarea has been calculated with formula (1). By using GIS the best suitable systems can be visualized on spatial level. Involving spatial information opens up opportunities for improving operational management and for advanced analyses.

2.3 Analysis of impacts

The evaluation of the results has been achieved via sensitivity analysis, which estimates the trade-offs as a result of changing weights of the evaluation criteria, and via spatial aggregation of the criteria. The latter aggregates the values of the evaluation criteria of the best suitable systems (estimated by utility analysis) for a defined area. The aggregation should determine the consequences of different treatment scenarios for a certain region and a certain planning period. The evaluation model enables the user to calculate the contribution to climate protection via prevention of greenhouse gas emissions, the contribution to the profit of the enterprise via improving of the value added, the contribution to full employment via increasing labour utilization, injury quotas, equipment and labour relocation time, and the demand of equipment and workforce. These data could also be used as an index for the evaluation of the quality of several harvesting treatments.

3. Results

3.1 Technological evaluation

Due to the fact that the investigation area (district Tiefental) is located in steep terrain, wheel-based systems can hardly be implemented. Only some small flat parts in the North can be utilized by “harvester-forwarder” technology (4 % of the area). The possibility of hauling the timber by skidders to the forest road increases the potential harvesting areas for the system “chain saw-skidder” up to 79 %. The potential area for manually skidding covers 56 % of district Tiefental. Tracked harvester in combination with cable forwarder can be implemented on 665 ha. As a result of the high road density cable yarders could be used in nearly all areas of Tiefental. Table 3 gives an overview of potential harvesting areas.

Table 3: Potential harvesting areas based on technological evaluation

Harvesting Systems	Potential Harvesting Area	
	ha	%
Chain saw & Helicopter & Processor	1098,37	100
Chain saw & Cable Yarder (& Processor)	1090,65	99
Chain saw & Cable Forwarder	677,30	62
Tracked Harvester & Cable Yarder/Forwarder	664,91	61
Chain saw & Manually skidding	616,20	56
Chain saw & Skidder	866,37	79
thereof ground skidding	*805,27*	*73*
Chain saw & Forwarder	61,10	6
Wheeled Harvester & Forwarder	48,72	4

3.2 Selection of harvesting systems

Based on the technological evaluation and environmental conditions, the utility analysis estimated 7 systems, which could be executed in the investigation area. "Tracked Harvester & Cable Forwarder" and "Chain saw & Cable Yarder & Processor" are the most favoured systems in the following example (Table 4). The spatial distribution of the harvesting systems can be seen in Figure 4.

Table 4: Absolute area and relative percentage of best suitable harvesting systems

Harvesting System	Area	Relative Percentage
Wheeled Harvester & Forwarder	1 ha	0 %
Tracked Harvester & Cable Yarder	5 ha	1 %
Tracked Harvester & Cable Forwarder	510 ha	58 %
Chain saw & Cable Forwarder	3 ha	0 %
Chain saw & Cable Yarder	48 ha	5 %
Chain saw & Cable Yarder & Processor	305 ha	35 %
Chain saw & Helicopter & Processor	7 ha	1 %

The dominance of the system "Tracked Harvester & Cable Forwarder" in areas with slopes < 60 % might be explained by following reasons:

- Less impacts on soil because of tracked travelling mechanism
- High system productiveness
- Moderate greenhouse gas emissions
- Moderate damage on remaining stand
- High value added
- Low equipment rotation times because of a high percentage of potential harvesting areas
- High working safety because of fully mechanized harvesting systems

The dominance of the system "Chain saw & Cable Yarder & Processor" in areas with slopes > 60 % might be explained by following reasons:

- Higher value added than other technologically suitable cable- or air-based systems
- Higher working safety than the system "Chain saw & Cable Yarder" in cut-to-length method

In this example technologically highly developed systems are more preferred than partly mechanised systems. If the trade-offs are not too high, operational work with chain saw will be prevented. Therefore the systems "Chain saw & Skidder" and "Chain saw & Forwarder" will not be estimated by the evaluation model. "Chain saw & Cable Yarder" in cut-to-length method will be proposed in steep terrain and high skidding distances. Skidding operations with helicopter will only be suggested if there is no other system applicable.

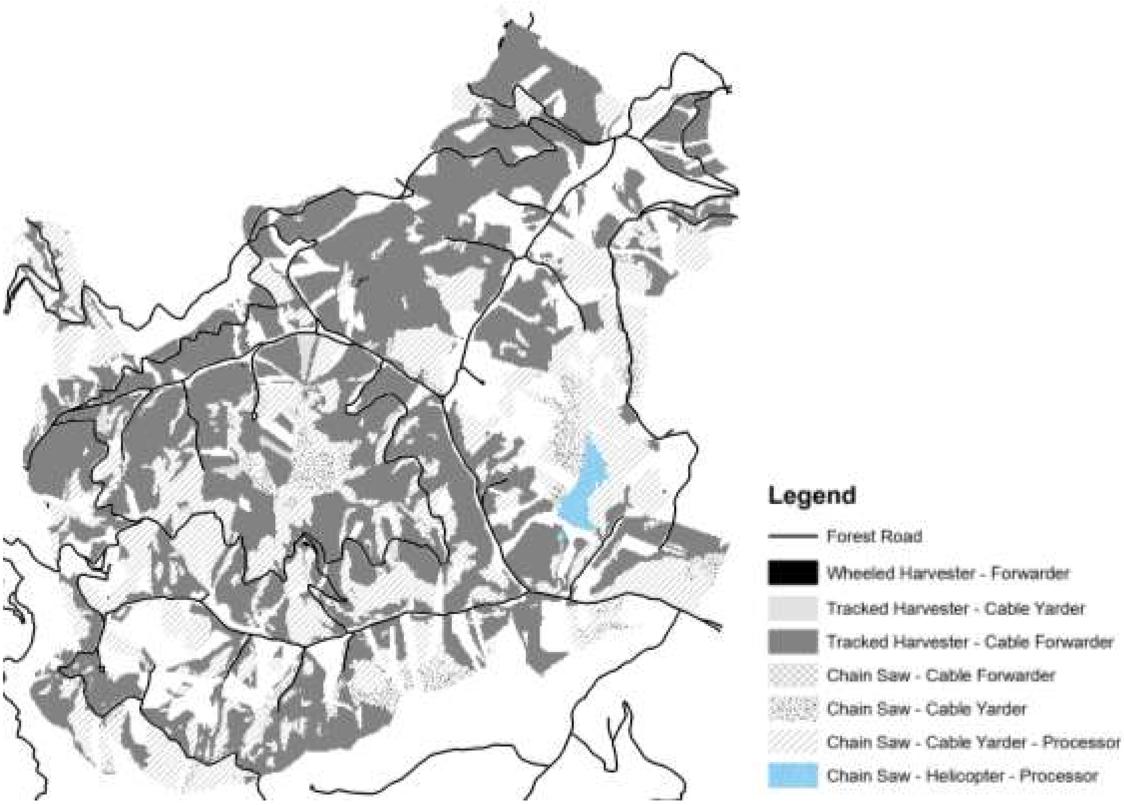

Figure 4: Spatial distribution of best suitable harvesting systems

3.3 Impacts of the harvesting program

One big advantage of the evaluation model is that the impacts of the proposed harvesting systems can be estimated immediately. In the chosen example the following effects has been calculated for an annual harvesting volume of 19.865 m³:

Table 5: Impacts of the harvesting program

Category	Area
Ø Greenhouse gas emissions in kg/m³	4,47
Ø Bearing Pressure in kPa	200
Ø Damage on remaining stand	25
Ø Value added in €/m³	47
Ø Employment in h/m³	0,30
Ø Injury rate per million m³	31,49
Employment in h/year	8.435 h
Capacity demand: Chain saw	4.287 h
Capacity demand: Tracked Harvester	549 h

Category	Area
Capacity demand: Cable Forwarder	505 h
Capacity demand: Cable Yarder	158 h
Capacity demand: Cable Yarder & Processor	1.239 h
Capacity demand: Helicopter & Processor	7 h

The bearing pressure is relatively high as a result of the big potential of operating areas of the cable forwarder. Damage on the remaining stand will be caused by the system "Chain saw & Cable Yarder & Processor" because of operating in whole-tree-method. The greenhouse gas emissions are also relatively high due to the heavy demand of fully mechanised systems. The model gives also the possibility to estimate the equipment and workforce demand, which accounts for 8.435 h manpower and 549 h operating time of tracked harvesters.

3.4 Example of demonstration: Implementation of new harvesting technologies

The main advantage of this model is the provision of additional information for the decision-making process and therefore reducing the risks of taking wrong measures with sustainably unfavourable impacts. The developed model can be used for analyses of several scenarios, e.g. the comparison of different treatment alternatives, the evaluation of previous or future utilisations, the impacts of changes in forest opening, or the determination of a minimum/maximum utilisation of equipment and work force.

The following table shows the impacts after implementing cable-forwarder technology. For the next ten years potential areas of 843 ha and an average volume of 19.865 m³/year are intended for harvesting operations. Without cable-forwarders 52 % of the harvesting volume will probably be utilised by "tracked harvester & cable yarder" and 38 % by "chain saw & cable yarder & processor".

Table 6: Harvesting volume before and after implementing cable forwarder technology

	Without cable forwarder	With cable forwarder
System	Harvesting Volume	Harvesting Volume
Wheeled Harvester & Forwarder	679 FM	12 FM
Chain saw & Manually skidding	140 FM	0 FM
Tracked Harvester & Cable Forwarder	-	11.067 FM
Chain saw & Cable Forwarder	-	52 FM
Tracked Harvester & Cable Yarder	10.323 FM	11 FM
Chain saw & Skidder	894 FM	894 FM
Chain saw & Cable Yarder & Processor	7.611 FM	7.611 FM
Chain saw & Helicopter & Processor	218 FM	218 FM
	19.865 FM	19.865 FM

After implementing “cable forwarder” technology 56 % of the harvesting volume could be utilised by “tracked harvester & cable forwarder”. This means that in areas with slope < 60 % cable yarders will almost fully replaced by cable forwarders.

Table 7 shows the impacts on the evaluation criteria before and after implementing cable forwarder technology. As a result of the steep terrain in district Tiefental the productivity is only slightly increasing. The higher impacts on the soil by cable forwarders involve a quadruplication of the average bearing pressure. Harvesting with cable forwarders takes more care to the remaining stand and produces less damage. By reasons of the higher productivity of cable forwarders and almost identical costs/hour the value added could be increased by 6 €/m³. As a result of the increased application of fully mechanised systems the injury rate could be decreased by more than 30 %. On the other hand employment effects are also decreasing by 35 %. After including all criteria the implementation of cable forwarder technology looks upon favourably.

Table 7: Impacts before and after implementing cable forwarder technology

Indicator	Without cable forwarder	With cable forwarder
Productivity	7 m³/h	8 m³/h
Bearing Pressure	50 kPa	200 kPa
Fuel Consumption	4,91 kg CO_2/m³	4,83 kg CO_2/m³
Stand Damage	29 %	27 %
Value Added	40 €/m³	46 €/m³
Demand in Work Force	0,51 h/m³	0,33 h/m³
Injury Rate	49,48/million m³	31,49/million m³

4. Conclusions

The model estimates the best suitable harvesting systems for a defined area and periods. For different scenarios and treatment alternatives the impacts can be calculated and compared quickly. Decision makers receive a tool to improve their information for forest management, which helps to reduce the risk of making unfavourable decisions. Admittedly, the quality of the results depends always on the quality and availability of the input data. To get satisfied outcomes stand and elevation data should have a high resolution. It is also important to know that the weighting of the scenarios might be different for every user because of the different preferences of the stakeholders. To involve different stakeholders voting theory could be implemented (Laukkanen et al. 2005).

Further development of the approach has been carried out, whereby the model will be tested in other investigation areas. Especially in flat terrain there are not many experiences available so far. In future times the model should also consider high-resolution LIDAR data. To improve the results more criteria in good quality will be implemented. To make the model more user-friendly the user interface and interaction control should also be improved. The practicability of this model for planning of opening-up and energy wood supply will be checked.

5. References

Kainulainen, T., Leskinen, P., Korhonen, P., Haara, A. 2007. A statistical approach to assess interval scale preferences in discerete choice problems. Manuscript.

Kangas, A., Kangas, J. & Kurttila, M. 2008: Decision support for forest management. -Berlin: Springer, XII, 222 p.

Laukkanen, S., Palander, T., Kangas, J. & Kangas, A. 2005: Evaluation of the multicriteria approval method for timber-harvesting group decision support. Silva Fennica, Volume 39, Issue 2, 2005, Pages 249-264.

Lexer, M.J., Vacik, H., Palmetzhofer, D. & Oitzinger, G., 2005: A decision support tool to improve forestry extension services for small private landowners in southern Austria. Computers and Electronics in Agriculture 49, 81-102.

Lüthy, D. 1998: Entwicklung eines "Spatial decision support"-Systems (SDSS) für die Holzernteplanung in steilen Geländeverhältnissen. - Zürich: Vdf, Hochschul-Verl. an der ETH. - 260 S. ISBN 3-7281-2654-3.

Mallinger, A. 2002: Technologieinventur. Berechnung von Potentialen in der Holzernte durch Rasterdatenanalyse und visuelles Programmieren mit „MapModels“. Projektarbeit UNIGIS 2000 (MAS), Institut für Geographie und Angewandte Informatik an der Universität Salzburg, 73 S.

Meyer, T., Stückelberger, J., Hollenstein, K., Attenberger, M. & Hänggli, T. 2001: effor2: Holzerntekonzept für die Untersuchungsbetriebe im Kanton Schwyz. Eidgenössiche Technische Hochschule Zürich. Interne Berichte Nr. 11. 98 S.

Saaty, T. L. 1977: A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 15: 234-281.

von Winterfeldt, D. & Edwards, W. 1986: Decision analysis and behavioral research. Cambridge University Press, Cambridge.

Yoshioka, T. & Sakai, H. 2005: Amount and availability of forest biomass as an energy resource in a mountainous region in Japan: a GIS-based analysis. Croatian Journal of Forest Engineering 26 (2005) 2. S. 59-68.