Development of a Multi-Attribute Spatial Decision Support System in Selecting Timber Harvesting Systems

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Abstract – Nacrtak

Strategic and tactical decisions in timber harvesting planning have long-term consequences on the further development of forests. Decisions about harvesting activities are often based on intuition and the consequences of these actions cannot be determined exactly. A GIS based evaluation model was designed to support the timber harvesting decision making process. It 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 area of interest is defined. Then, a technological evaluation of harvesting systems capability determines their compatibility with location factors. Only acceptable systems are included into the third stage, the utility analysis. Using evaluation criteria, it transforms them into comparable values and ranks these values. The last stage of the model provides a metric that estimates consequences of different treatment scenarios. The main processes have been automated in ESRI® ArcGIS by using ModelBuilder™ extension. The model has been demonstrated in a 1100 ha sized forest enterprise in steep terrain in the South of Lower Austria. One scenario determined the possible benefits of implementing »cable forwarders« as new harvesting technology. Five of seven criteria could be improved; including a reduction of stand damage by 2 percent points and an increase of contribution margin from 40 to 46 €/m³. Improving forest road network generated a positive effect on productivity and fuel consumption, but the overall economic benefit was too low to recommend the construction of the road. The model suggests that a combination of increasing forest road density and technology improvement could lead to tripling productivity, increasing contribution margin from 40 to 56 €/m³ and lowering the damage rate by 53% and injury rate by 93%. This example shows that this SDSS can help the user to determine the best suitable alternatives.

Keywords: timber harvesting, forest road network, decision support, evaluation model, utility analysis

1. Introduction – *Uvod*

Timber harvesting is often one of the main objectives of forest management. It increases the contribution margin to the forest enterprise, but can also have positive effects on long-term ecological and social values. Efficient harvesting operations are based on a well established forest road network, best suitable equipment and machines and experienced forest workers (Stampfer 2010). Decisions in selecting these items are mostly based on experience and intuition and often do not consider a long-term and sustainable strategy of resource management (Lüthy 1998). Such a decision making process can cause difficulty when reacting to change, e. g. in harvesting volume or technology. Admittedly, the increase in production costs and the development of new technologies presupposes a continuous review of the systems used.

To estimate the effects of changes in management a decision support tool is helpful, especially for tactical and strategic goals. Changing forest road network or using different harvesting systems can have large consequences on costs, ecological and social impacts and machine and work force capacity. Until now, economic efficiency has been the most important criterion for selecting harvesting systems (Lüthy 1998, Meyer et al. 2001, Lubello 2008). The non-consideration of ecological and social criteria may impose negative side-effects and risks that revoke the economic advantage. Therefore, a well-grounded analysis of harvesting systems should take stand and terrain data as well as ecological, economic and social impacts into account (Mendoza 1989, Næsset 1997, Sheppard et al. 2005, Wolfslehner et al. 2008, Kangas et al. 2008). Since this decision problem consists of several criteria and bears many trade-offs, a satisfactory solution can hardly be found without using technical and mathematical tools. For that reason a multi-criteria, computer-aided DSS is a good approach (Vacik and Lexer 2001, Lexer et al. 2005, Kangas and Kangas 2005). Harvesting operations are carried out at a spatial level and are best considered using GIS technology. Equipment and work force have to be transported to the operation 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 roughness of the terrain.

In recent years some studies have been published to estimate best suitable harvesting systems on the basis of forest districts or compartments. Lüthy (1998) focused on the development of a SDSS concerning harvesting system evaluations in steep terrain. The case study included a technological evaluation and rough cost estimation. Yoshioka and Sakai (2005) analyzed the amount and availability of forest biomass as an energy resource in mountainous regions. This study was based on a GIS analysis including three machinery types (skidder, tower yarder, and sledge yarder) and three biomass resources (logging residues, thinned trees, and broadleaved forests). The resources with the lowest procurement costs were selected. Lubello (2008) implemented a GIS-based SDSS for extracting operations. The model outputs show feasible working areas of each system (skidder, forwarder, cable forwarder, tower yarder, sledge yarder), and the technical and optimized distribution of systems with costs. A similar approach was made by Adams et al. (2003) for 500 hectares of mountainous terrain in south–west Virginia. They analyzed harvest system allocations for wheeled skidder, tracked skidder, cable yarder and helicopter. In Austria a technological evaluation of harvesting systems based on stand and terrain data has been carried out by Mallinger (2002). Nevertheless, none of these studies took ecological or social criteria into account, which is essential for a comprehensive analysis of the impacts of harvesting operations.

The aim of this study is to develop a SDSS for identifying best suitable harvesting systems and to estimate ecological, economical and social consequences of timber harvesting operations. The main focus of the model is on improving forest road networks and/or implementing new harvesting technologies.

2. Materials and methods – *Materijal i metode*

2.1 SDSS architecture – *Arhitektura SDSS-a*

2.1.1 Development approach – *Pristup razvoju*

A master model was developed that involved iterative communication and negotiating among the users; the decision analyst and the software engineer that together define the decision scope and decision-making process (Lexer et al. 2005). This master model combines different but related aspects of the DSS-development. For example, the process model represents the flow of data and information througthout the modelled planning and decision-making process, and describes the exchange of information among various DSS components. The formal model includes the algorithms, rules, and mathematical equations needed to formally describe the modelled system. Finally, the software engineer has to create the implementation model, which comprises software architecture and technical solutions to implement the master model (Lexer et al. 2005). Based on iterative discussions and a negotiation process, the major processes of the master model were developed (Fig. 1).

2.1.2 Dividing the decision problem – *Podjela problema odlučivanja*

The basic decision problem can be divided into two parts:

⇒ (a) which harvesting systems are suitable at particular locations within a defined project area,

⇒ (b) which harvesting system is the best suitable when including considerations of economic, ecological and social effects.

The master model was designed so that both questions could be analyzed successively but within the same general analytical process. The decision process includes a set of medium to long-term objectives for the management of timber harvesting. The evaluation process within the master model is made up of four stages. First, the investigation area has to be defined. In the next step a technological evaluation of harvesting systems is implemented, where the capability of harvesting systems is determined by comparing their specification data with location factors (Löffler 1984). Concordant systems are in-

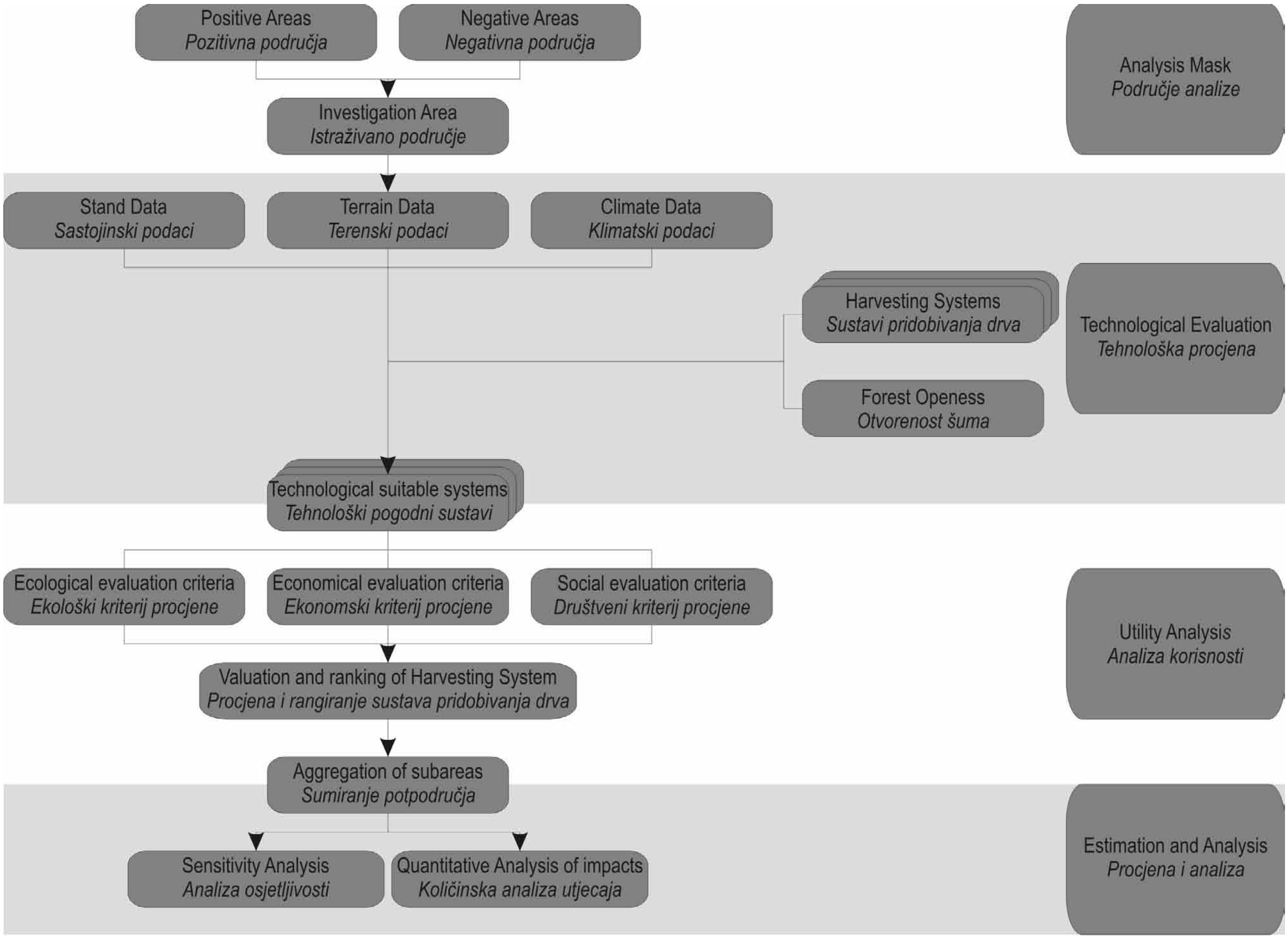

Fig. 1 Schematic representation of the main processes of the master model
Slika 1. *Shematski prikaz glavnih procesa glavnoga modela*

cluded 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.

2.1.3 Analysis mask – *Područje analize*

For estimating potential timber harvesting areas, desirable zones (e. g. forests) have been intersected with non-desirable (protected or prohibited areas). This combination of data layers generated the analysis mask for technological evaluation and utility analysis.

2.1.4 Creating technological layers – *Određivanje tehnoloških pokazatelja*

10 different harvesting systems have been taken into account for the technological evaluation. They differ in four grades of mechanization and three working methods (Stampfer 2002). For the technological evaluation, four criteria have been chosen. They act as specification data for the applicability of the selected harvesting system under given site conditions. 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 soil bearing capacity. The extraction distance is a limiting factor for cable-supported machines, e. g. tower yarders (400 m) and skidders (100 m). The limiting DBH for harvester and processor depends on the type of harvesting head. A strongly varying morphology is a restricting factor for ground-based systems as a result of reduced trafficability. According to the extraction operation, harvesting systems can be divided into cut-to-length (CTL), tree-length (TL) and whole-tree (WT) methods (Table 1).

By combining stand and terrain conditions with the equipment specifications, a »technology layer« has been calculated for every harvesting system. To

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

Tablica 1. *Sustavi pridobivanja drva i strojevi koji se odnose na sastojinske i terenske podatke*

Harvesting System – *Sustav pridobivanja drva*		Technological Specification – *Tehnološke značajke*
1	Chain saw & Wood-pick, CTL *Motorna pila i capin; sortimentna metoda*	Slope 30–60%, Terrain accessible *Nagib terena 30–60 %, pristupačan teren*
2	Chain saw & Forwarder, CTL *Motorna pila i forvarder; sortimentna metoda*	Slope < 30%, Terrain accessible *Nagib terena < 30 %, pristupačan teren*
3	Chain saw & Cable Forwarder, CTL *Motorna pila i forvarder s vitlom; sortimentna metoda*	Slope < 60%, Terrain accessible *Nagib terena < 60 %, pristupačan teren*
4	Chain saw & Skidder, TL *Motorna pila i skider; deblovna metoda*	Slope < 30%, Terrain accessible *Nagib terena < 30 %, pristupačan teren*
5	Wheeled Harvester & Forwarder, CTL *Kotačni harvester i forvarder, sortimentna metoda*	Slope < 30%, Terrain accessible, DBH max. 40 cm *Nagib terena < 30 %, pristupačan teren, prsni promjer maks. 40 cm*
6	Tracked Harvester & Tower Yarder, CTL *Gusjenični harvester i stupna šumska žičara; sortimentna metoda*	Slope < 60%, Extraction distance < 800 m, Terrain accessible, DBH max. 40 cm *Nagib terena < 60 %, srednja udaljenost privlačenja < 800 m, pristupačan teren, prsni promjer maks. 40 cm*
7	Tracked Harvester & Cable Forwarder, CTL *Gusjenični harvester i forvarder s vitlom; sortimentna metoda*	Slope < 60%, Terrain accessible, DBH max. 40 cm *Nagib terena < 60 %, pristupačan teren, prsni promjer maks. 40 cm*
8	Chain saw & Tower Yarder, CTL *Motorna pila i stupna šumska žičara; sortimentna metoda*	Slope < 100%, Extraction distance < 400 m *Nagib terena < 100 %, pristupačan teren, srednja udaljenost privlačenja < 400 m*
9	Chain saw & Tower Yarder & Processor, WT *Motorna pila, stupna šumska žičara i procesor; stablovna metoda*	Slope < 100%, Extraction distance <400 m *Nagib terena < 100 %, srednja udaljenost privlačenja < 400 m*
10	Chain saw & Helicopter & Processor, TL *Motorna pila, helikopter i procesor; deblovna metoda*	-

move machines of ground-based systems to the utilization area the harvesting sites have to be accessible. This means that machines are able to drive to the harvesting site. If not, and generally usable zones were surrounded by non-usable ones, these areas have been shifted to the next possible technology layer. Furthermore climate data could be considered to determine periods without the possibility of carrying out harvesting operations as a result of high snow cover, and to estimate advantageous periods for trafficability caused by frozen underground. The technology layers act as input data for the next step – the utility analysis.

2.1.5 A multiple criteria utility model to evaluate alternatives – *Višekriterijski model korisnosti za procjenu zamjenskih rješenja*

To evaluate the overall utility of decision alternatives for cases where there is more than one possible solution, an approach borrowed from multiple-attribute utility theory (MAUT) was adopted. This method requires the mathematical characterization of the preferences of the decision maker over a set of attributes (Goicoechea et al. 1982). In a case of MAUT, it is assumed that there are a certain number of criteria (m) 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 trade-offs between the criteria (Kangas et al. 2008). The best suitable alternative is the one with the highest overall utility. The most applied multi-attribute utility function is the linear additive utility function.

$$U_i = \sum_{j=1}^{m} a_j c_{ij} \tag{1}$$

where:

U_i describes the overall utility of alternative i (or priority of alternative i)

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:

$$\sum_{j=1}^{m} a_j = 1 \tag{2}$$

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 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. one goal does not influence the performance of another goal. Indicators are variables, which indicate the status of criteria. For the evaluation model, ecological criteria (impacts on soil, global warming potential, stand damage), economic criteria (contribution margin, relocation time) and social criteria (employment, working safety) have been chosen. Criteria (bold) and indicators are presented in Table 2.

The calculation of the absolute values of the criteria either depends on machines and/or system (e.g. impacts on soil, stand damage, working safety); or on both system and stand data (all other criteria). The latter are based on productivity models, which also include a mode for tree volume, slope and extraction distance (Stampfer 2002, Kühmaier 2010). The criteria values have been scaled by preference functions. There are several methods for estimating preference functions. In this study the natural scale values have been scaled with score range procedure for all data within the project area (Kangas et al. 2008).

$$v_i = (c_i - \min(c)) \ / \ (\max(c) - \min(c)) \quad (4)$$

The best alternative is assumed to have a value of 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 the interval depends on specific planning situation (Kainulainen et al. 2007). As an example, the linear preference function for the criterion »contribution margin« has a value of zero below –20 €/m³ and a value of one above 100 €/m³ (Fig. 2).

In direct weighting 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 Ed-

Table 2 Harvesting systems and equipment subject to stand and terrain data

Tablica 2. *Sustavi pridobivanja drva i strojevi koji se odnose na sastojinske i terenske podatke*

Criterion – ***Uvjeti*** Indicator – *Pokazatelji*	Input Data – *Ulazni podaci*	Source/Calculation *Izvor/Izračun*
Impacts on Soil – ***Utjecaj na tlo*** Bearing Pressure in kPa – *Nosivost tla*, kPa	Machine Weight – *Težina stroja* Tyre Dimension – *Dimenzija guma*	Rowland 1972 Maclaurin 2000 Suvinen 2006
Global Warming Potential – ***Potencijal globalnoga zagrijavanja*** Fuel Consumption in kg CO_2-Equivalent – *Potrošnja goriva u kg ekvivalent* CO_2	Fuel Consumption – *Potrošnja goriva* System Productivity – *Proizvodnost sustava*	Nordfjell et al. 2003 Klvac et al. 2009 Berg & Lindholm 2005
Stand Damage – ***Oštećenost sastojine*** Damage on Remaining Stand in % – *Oštećenost preostaloga dijela sastojine*, %	Damage per Harvesting System *Oštećenost po sustavu pridobivanja drva*	Stampfer 2002 Limbeck-Lilienau 2004 Wratschko 2006
Contribution Margin – ***Kontribucijska marža*** Contribution Margin in €/m³ – *Kontribucijska marža*, €/m³	Revenues – *Prihodi* Hourly System Costs – Troškovi sustava po satu System Productivity – *Proizvodnost sustava*	Sterba 1983 Stampfer 2009
Relocation Time – ***Vrijeme premještanja*** Aggregation of Harvesting Areas in % – *Zbroj po sječinama*, %	Technological Layers *Tehnološki pokazatelji*	See chapter 2.1.4
Employment – ***Zaposlenost*** Demand in Work Force in h/m³ – *Potreba za radnom snagom*, h/m³	Demand in Work Force *Potreba za radnom snagom* System Productivity – *Proizvodnost sustava*	Stampfer 2009 Stampfer 2010
Working Safety – ***Sigurnost pri radu*** Accidents in n/m³ – *Broj nezgoda*, n/m³	Injury rates – *Broj ozljeda*	Manwaring et al. 1998 Jänich 2009 Eiwegger 2009

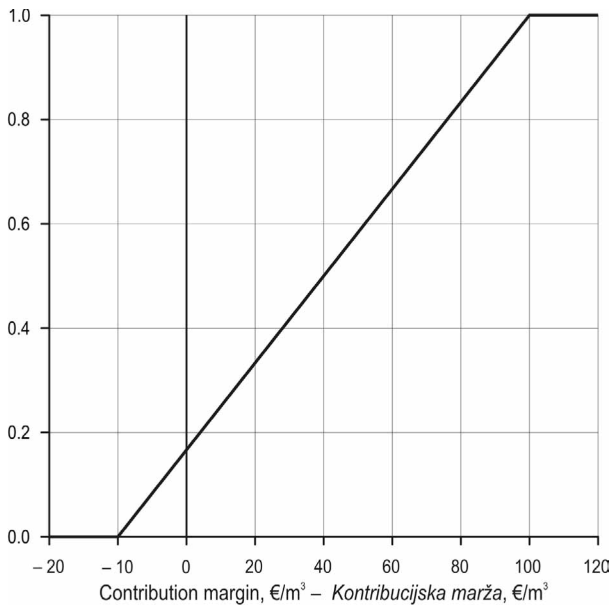

Fig. 2 Value function for »contribution margin«
Slika 2. *Vrijednosna funkcija za kontribucijsku maržu*

wards 1986, Saaty 1977). The overall utility for each alternative (harvesting system) and for each subarea has been calculated with Equation (1). The best suitable harvesting system is the one with the highest overall utility calculated for each subarea (e.g. stand, raster cell). The spatial allocation of the best suitable harvesting systems can be viewed directly on the screen.

2.1.6 Analysis and comparison of treatment scenarios – *Analiza i usporedba scenarija postupaka*

The overall effects of the evaluation process have been calculated by spatial aggregation of the evaluation criteria. For the aggregation, only the values of the best suitable harvesting systems (estimated by utility analysis) within the project area have been included for a certain planning period. The evaluation model within the SDSS enables the user to calculate the benefits to climate protection by reduction of greenhouse gas emissions, the contribution to the enterprise profit, the contribution to full employment by 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.

2.2 Model implementation – *Primjena modela*

GIS software was used to implement the model. The main processes have been automated in ESRI® ArcGIS by using the ModelBuilder™ extension. Supporting calculations have been carried out in Microsoft® Excel and Microsoft® Access. The necessary analogue data has been digitised and together with the digital information they have been harmonized in GIS by using the same projection and connecting them by primary index. Analyses in GIS are based on raster calculations. The configuration of all the calculations is composed of modules that have been generated with the ModelBuilder™ extension based on Python scripts. ModelBuilder™ is an application in ArcGIS that allows creation, editing and management of models. Models give the possibility to automate the workflow and to execute calculations multiple times. The idea behind using this calculation is to make calculations easier, to chain together workflows by using the output of one tool as the input to another tool, but also to have some possibilities to check the intermediary results. The created models have been implemented in ESRI® ArcToolbox. The GUI is similar to the standard software ESRI® ArcGIS, but with additional features and a help function. The models can be executed in the Toolbox using its dialog or the Command Line window.

2.3 Project area – *Područje istraživanja*

The SDSS was demonstrated for a region of approximately 1100 ha in the South of Lower Austria (15°39′ longitude East, 47°52′ latitude North). This region is called Tiefental with a main elevation of 800 m. According to Kilian et al. (1994) beech forests (*Fagus sylvatica* L.) with fir (*Abies alba* Mill.), sycamore (*Acer pseudoplatanus* L.) and ash, spruce-fir-beech forests (*Picea abies* L.) and spruce-fir forests with oak (*Quercus robur* L.) are the natural vegetation composition. On shallow and exposed dolomite soils, pine forests (*Pinus sylvestris* L.) are expected. The climate is characterized by cold winters with average January temperatures of –2.6° C, and hot summers with average July temperatures of 15.5° C. The annual average temperature is 6.5° C. The average annual precipitation is about 1300 mm. Depending on the sea level, the duration of the snow cover ranges from 50 to 140 days. 93% of the area is located on calcareous sites and 7% on recent landfills. 10.5% of the forest area is provided on flat terrain (< 30%), and 23% is located in steep terrain (> 60%). Current forests in the project area are dominated by Norway spruce (59.5%) and Scots pine (24.7%) and European larch (7.1%) and broadleaved trees (8.3%) with less importance as crop species. The utilization method is based on small-area operations and single tree forest management systems. Natural regeneration is preferred. The annual cut is about 5350 m³ of timber, transported on forest roads with a density of approximately 34.8 running meters per ha.

Table 3 Criteria weighting
Tablica 3. *Težinski faktori obilježja*

Criterion *Obilježje*	Impacts on Soil *Utjecaj na tlo*	Global Warming Potential *Potencijal globalnoga zagrijavanja*	Stand Damage *Oštećenost sastojine*	Contribution Margin *Kontribucijska marža*	Relocation Time *Vrijeme premještanja*	Employment *Zaposlenost*	Working Safety *Sigurnost pri radu*
Weight Težina	5%	10%	15%	35%	5%	10%	20%

3. Results – *Rezultati*

The evaluation process analyzed the best suitable harvesting systems for four scenarios within the Tiefental region:

⇒ (a) before implementing cable forwarder technology and before improving forest road network,

⇒ (b) after implementing cable forwarder technology,

⇒ (c) after improving forest road network,

⇒ (d) combining b and c.

Scenario a is used as a zero option and will be compared with all other scenarios. For the Tiefental SDSS the weighting of the criteria has been done in the following way: Contribution margin is the most important criteria, followed by working safety and stand damage. Global warming potential, employment, impacts on soil and relocation time have minor importance with a weighting factor of 5 to 10% (Table 3). These preferences have been developed together with the forest managers of Tiefental region.

3.1 Scenario b: Implementing cable forwarder technology – *Scenarij b: Primjena forvardera s vitlom*

The project area is characterised by steep terrain so that wheel-based systems can hardly be implemented. Only in some small flat parts in the Northern region, »harvester-forwarder« technology can be used. The potential of extracting timber with a forwarder is about 6% of the project area, but the possibility of extracting timber with a skidder to the forest road increases the potential harvesting area for the system »chainsaw-skidder« up to 79%. Hand delivery could be implemented on moderately sloped areas that cover 56% of Tiefental region. Tracked harvester in combination with cable forwarder might be used on 665 ha. As a result of excellent road density within the project area, tower yarders could be used in nearly all areas of Tiefental (Table 4). Advantageous periods for trafficability caused by frozen underground and no or low snow cover comprises approximately three weeks from the end of November till mid-December. From mid-December till the end

Table 4 Potential harvesting areas based on technological evaluation for scenario b
Tablica 4. *Moguće sječine zasnovane na tehnološkoj procjeni scenarija b*

Technological layer – *Tehnološki pokazatelj*	Potential Harvesting Area *Moguće područje pridobivanja drva*	
	ha	%
Chain saw & Helicopter & Processor – *Motorna pila, helikopter i procesor*	1098	100
Chain saw & Tower Yarder (& Processor) – *Motorna pila, stupna šumska žičara i procesor*	1091	99
Chain saw & Cable Forwarder – *Motorna pila i forvarder s vitlom*	677	62
Tracked Harvester & Tower Yarder/Cable Forwarder – *Gusjenični harvester i stupna šumska žičara/forvarder s vitlom*	665	61
Chain saw & Wood-pick – *Motorna pila i capin*	616	56
Chain saw & Skidder – *Motorna pila i skider*	866	79
There of skidding from forest road – *Od toga po tlu kretnim sustavima*	805	73
Chain saw & Forwarder – *Motorna pila i forvarder*	61	6
Wheeled Harvester & Forwarder – *Kotačni harvester i forvarder*	49	4

Table 5 Harvesting volume before and after implementing cable forwarder technology
Tablica 5. *Sječivi obujam prije i poslije uvođenja forvardera s vitlom*

System – *Sustav*	Scenario a – *Scenarij a*		Scenario b – *Scenarij b*	
Wheeled Harvester & Forwarder – *Kotačni harvester i forvarder*	183 m³	3%	3 m³	0%
Chain saw & Wood-Pick – *Motorna pila i capin*	38 m³	1%	0 m³	0%
Tracked Harvester & Cable Forwarder – *Gusjenični harvester i forvarder s vitlom*	0 m³	0%	2983 m³	56%
Chain saw & Cable Forwarder – *Motorna pila i forvarder s vitlom*	0 m³	0%	14 m³	0%
Tracked Harvester & Tower Yarder – *Gusjenični harvester i stupna šumska žičara*	2782 m³	52%	3 m³	0%
Chain saw & Skidder – *Motorna pila i skider*	241 m³	5%	241 m³	5%
Chain saw & Tower Yarder & Processor – *Motorna pila, stupna šumska žičara i procesor*	2051 m³	38%	2051 m³	38%
Chain saw & Helicopter & Processor – *Motorna pila, helikopter i procesor*	59 m³	1%	59 m³	1%
	5354 m³	100%	5354 m³	100%

of March harvesting is normally not possible because of too high snow cover.

843 ha of forest covered area and an average volume of 5354 m³/year are intended for harvesting operations within the next ten years in the Wittgenstein region. Cable forwarders are forwarders equipped with a winch, which increases traction control during extraction operations. The model suggests that with this technology the range of application for forwarders has been boosted up to more than 60%. Given the steep terrain in the project area, extracting with tower yarder was the most favourable extraction operation. 90% of timber was to be harvested with this technology. After introducing cable forwarder technology, the composition of the best suitable harvesting systems, as suggested by the model output, has changed dramatically within regions with slope range of 30 to 60%. 56% of the potential harvesting volume could then be harvested by »tracked harvester & cable forwarder« (Table 5).

After this technological innovation in areas with slope < 60%, all other harvesting systems will be almost fully replaced by cable forwarders (Fig. 3).

The applicability of cable forwarders in areas with slopes < 60% might be explained by fewer impacts on the remaining stand because of a more careful extraction process, higher system productivity and no setup times, fewer greenhouse gas emissions, higher contribution margin because of lower harvesting costs, fewer equipment rotation times, and higher working safety as a result of fully mechanized harvesting systems. On the other hand, the impacts on the soil increase because of higher bearing pressure of heavy cable forwarders and less people could be employed for harvesting the same timber volume. In the Tiefental region the productivity has only slightly increased after implementing cable forwarder technology, with contribution margin increased by 6 €/m³. By reasons of the increased application of fully mechanised systems the injury rate could be decreased by 36%. On the other hand employment effects are also decreasing by 35%. After taking into account all criteria, the implementation of cable forwarder technology looks favourable (Table 6).

In this example technologically highly developed systems are more preferred than partially mecha-

Table 6 Impacts before and after implementing cable forwarder technology
Tablica 6. *Utjecaji prije i poslije uvođenja forvardera s vitlom*

Indicator – *Pokazatelji*	Scenario a – *Scenarij a*	Scenario b – *Scenarij b*	Variation – *Varijabilnost*
Productivity – *Proizvodnost*	7 m³/h	8 m³/h	+14%
Bearing Pressure – *Nosivost tla*	50 kPa	200 kPa	+300%
Fuel Consumption – *Potrošnja goriva*	4.91 kg CO_2/m³	4.83 kg CO_2/m³	–2%
Stand Damage – *Oštećenost sastojine*	29%	27%	–7%
Contribution Margin – *Kontribucijska marža*	40 €/m³	46 €/m³	+15%
Demand in Work Force – *Potreba za radnom snagom*	0.51 h/m³	0.33 h/m³	–35%
Injury Rate – *Učestalost ozljeda*	49.48/million m³	31.49/million m³	–36%

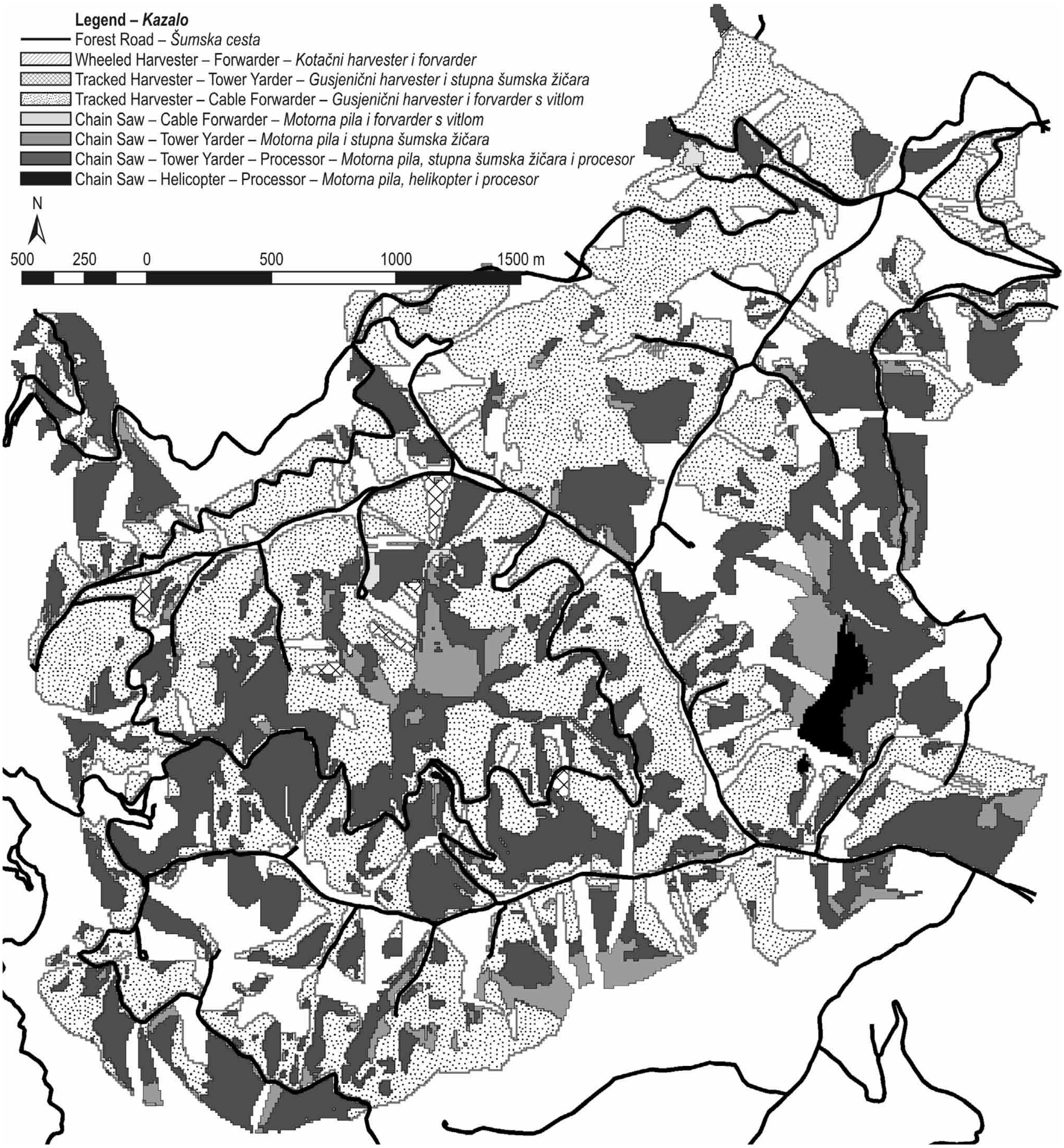

Fig. 3 Example of the Model map showing spatial distribution of best suitable harvesting systems after implementing cable forwarder technology
Slika 3. *Primjerna modelna karta s prostornom raspodjelom najpogodnijih sustava pridobivanja drva nakon uvođenja u primjenu forvardera s vitlom*

nised 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« are not likely in the evaluation model. »Chain saw & Tower Yarder« in cut-to-length method will be proposed only in steep terrain and high extraction distances. Extraction operations with helicopter will only be suggested if there is no other system applicable. The model also gives the possibility to estimate the equipment and work-

Table 7 Equipment and workforce demand

Tablica 7. *Zahtjevi za stojevima i radnom snagom*

Category – *Kategorija*	h/year
Employment (Work force) – *Zaposlenost (radna snaga)*	2273 h
Capacity demand: Chain saw *Uporaba: motorna pila*	1155 h
Capacity demand: Tracked Harvester *Uporaba: gusjenični harvester*	148 h
Capacity demand: Cable Forwarder *Uporaba: forvarder s vitlom*	136 h
Capacity demand: Tower Yarder *Uporaba: stupna šumska žičara*	43 h
Capacity demand: Tower Yarder & Processor *Uporaba: stupna šumska žičara i procesor*	334 h
Capacity demand: Helicopter & Processor *Uporaba: helikopter i procesor*	2 h

force demand, which accounts for 2273 h of manpower and 136 h of operating time for cable forwarders (Table 7).

3.2 Scenario c and d: Improving forest road network – *Scenariji c i d: poboljšanje mreže šumskih cesta*

The implementation of a new harvesting technology might be a good opportunity to improve the conditions of harvesting operations, but in non-accessible regions this would have no effect. Investing in infrastructure, higher road density has positive effects on the productivity of harvesting operations because of reduced extraction distance. The following example shows the effects of improving forest road network for an 11 ha area in Tiefental region, which can only be harvested by tower yarders or helicopter. There have been no harvesting operations in recent years, so there is 2595 m^3 available for harvesting within the next 20 years. The new forest road gives the possibility to improve currently used systems and to open the area for new harvesting technologies. Before improving the road network, the technological layers for the scenarios a, b and c are identical. Only tower yarders and helicopters can be used for extracting timber.

Before building the forest road, chain saw / tower yarder and chain saw / tower yarder / processor have been selected as best suitable harvesting systems by the model (Scenario a / b / c – Table 8). For these three scenarios the proposed systems are identical, but the impacts on the evaluation criteria may differ. After building the new road, the whole harvesting area is accessible for cable forwarder but also for tracked harvester technology and the utility analysis suggested using these two machine types for the whole area (Scenario d – Table 8).

After implementing the new forest road (Scenario c), the timber harvesting productivity could be increased by 50% in comparison to zero option (Scenario a). This increase is the result of the shorter average extraction distance, which could be reduced from 400 to 150 m. Further effects of higher productivity are lower fuel consumption, higher contribution margin, but also a lower employment rate. There is no difference between scenario a and b because in this area cable forwarder technology can only be used after road construction. The effects after implementing both new forest road and cable forwarder technology (Scenario d) were much more impressive. Productivity could be tripled. Fuel consumption, damage to the remaining stand and the injury rate were also much lower. These could be explained in using more efficient equipment and in the safety standards and better control mechanism of highly mechanised systems. On the other hand, there are also some negative effects, e.g. much higher bearing pressure after driving in the stand and lower demand in work force as a result of improved technology (Table 9).

After harvesting the whole timber volume with Scenario d, CO_2 emissions could be reduced by 5059 kg compared to scenario a / b. Contribution margin also increased by approximately EUR 40 000, but the employment rate decreased by 1330 hours. Although

Table 8 Harvesting volume before and after improving forest road network

Tablica 8. *Sječivi obujam prije i poslije poboljšanja mreže šumskih cesta*

System – *Sustav*	Scenario a/b/c – *Scenarij a/b/c*		Scenario d – *Scenarij d*	
Tracked Harvester & Cable Forwarder – *Gusjenični harvester i forvarder s vitlom*	0 m^3	0%	2595 m^3	100%
Chain saw & Tower Yarder – Motorna pila i *stupna šumska žičara*	834 m^3	32%	0 m^3	0%
Chain saw & Tower Yarder & Processor *Motorna pila, stupna šumska žičara i procesor*	1761 m^3	68%		0%
	2595 m^3	100%	2595 m^3	100%

Table 9 Impacts before and after improving forest road network

Tablica 9. *Utjecaj prije i poslije poboljšanja mreže šumskih cesta*

Indicator – *Pokazatelji*	Scenario a *Scenario a*	Scenario c *Scenario c*	Variation *Varijabilnost*	Scenario d *Scenario d*	Variation *Varijabilnost*
Productivity – *Proizvodnost*	6 m^3/h	9 m^3/h	+50%	19 m^3/h	+217%
Bearing Pressure – *Nosivost tla*	15 kPa	15 kPa	±0%	332 kPa	+2113 %
Fuel Consumption – *Potrošnja goriva*	5.93 kg CO_2/m^3	5.10 kg CO_2/m^3	–14%	3.98 kg CO_2/m^3	–33%
Stand Damage – *Oštećenost sastojine*	36%	36%	±0%	17%	–53%
Contribution Margin – *Kontribucijska marža*	40 €/m^3	48 €/m^3	+20%	56 €/m^3	+40%
Demand in Work Force – *Potreba za radnom snagom*	0.62 h/m^3	0.51 h/m^3	–18%	0.11 h/m^3	–82%
Injury Rate – *Učestalost ozljeda*	84.05/mil. m^3	84.05/mil. m^3	±0%	6.03/mil. m^3	–93%

Table 10 Cost analysis of forest road network improvement

Tablica 10. *Analiza troška poboljšanja mreže šumskih cesta*

	Scenario a *Scenarij a*	Scenario c *Scenarij c*	Scenario d *Scenarij d*
Contribution margin/year before road construction – *Kontribucijska marža prije izgradnje šumske ceste*	**5190 €**	6228 €	7226 €
Yearly payment – *Godišnji trošak*	-	1379 €	1379 €
Contribution margin/year after road construction – *Kontribucijska marža godinu dana nakon izgradnje šumske ceste*	-	**4849 €**	**5887 €**
Difference against Scenario a/b – *Razlika između slučaja a i b*	-	–341 €	697 €
Recommendation – *Preporuka*	-	negative	positive

five of seven criteria could be improved and the evaluation process suggests the implementation of cable forwarder technology, the overall evaluation of building a forest road does not need to be positive at all. Therefore also the effects of the construction phase should be implemented into the evaluation.

These results have further been validated by an economic evaluation. As part of the model, the contribution margin has been calculated for the area of interest by using average revenues, hourly system costs and productivity models (Kühmaier 2010). The construction of the forest road in the Tiefental region involves costs of approximately EUR 28 per running meter. To access the area, a new forest road with a total length of 700 m is required, resulting in an overall planned forest road cost of EUR 19 600. Considering a payment schedule period of 20 years and a yearly nominal interest rate of 3.5% an ordinary annuity of EUR 1379 has been estimated (Table 10).

After considering the yearly contribution margin before forest road construction and deducting the annual payments, a contribution margin between EUR 4849 and EUR 5887 has been calculated. The research shows that harvesting operations with the suggested systems are always positive within the investigation area. From an economic view, scenario d is the most favourable one, followed by a/b and c. These results show that an improving forest road network could enhance timber harvesting operations, but the payments for the road construction might not be settled within the investigation period and this will have a negative recommendation for upgrading infrastructure and efficiency in forest operations. Therefore, it is important to go one step further and also to include possible technological improvements, which can only be implemented after upgrading infrastructure. In our example, positive effects of scenario d can be seen against all other scenarios as a result of including infrastructure and technology improvement. Scenario d achieves a yearly contribution margin of EUR 5887, which is more than EUR 1000 higher than building the forest road without technology improvement, and EUR 700 higher than the zero option.

4. Summary – *Zaključci*

The aim of this study was to develop a SDSS for identifying the best suitable harvesting systems and to estimate ecological, economical and social effects on timber harvesting operations after improving forest road networks and/or implementing new harvesting technologies. The model has been implemented in GIS and demonstrated in a 1100 ha forest enterprise in steep terrain in the Southern part of Lower Austria. In evaluating specific scenarios, the implementation of cable forwarder technology had positive effects on productivity, CO_2 emissions, stand damage, contribution margin, and injury rate. On the other hand, the introduction of this technology had negative effects on the bearing capacity and employment rate. Generally speaking, the introduction of cable forwarders would have more positive than negative effects.

For another project area of 11 ha, the improvement of the forest road network also generated positive effects on productivity, fuel consumption and contribution margin, but the economic effect was too low to recommend the construction of the road. Only a combination of increasing forest road density and implementing cable forwarder technology lead to a positive decision with tripling productivity, increasing contribution margin from 40 to 56 €/m^3 and lowering the damage rate by 53% and the injury rate by 93%. Admittedly, impacts on soil and the employment rate deteriorated. This example also shows the need of involving both infrastructure and technology improvement for planning harvesting operations.

As with any multiple-attribute preference model, this approach generates a cardinally scaled order of all decision alternatives with respect to their expected utility. However, the decision maker must be aware that the resulting solution may just be a best-compromise solution based on subjective rationality (Mollaghasemi and Pet-Edwards 1997). Sensitivity analysis is one of the powerful tools of decision support systems. However, the implementation of this decision model in GIS has to be modified by an experienced user. By using a model base management system (MBMS) and storing model components in an object-oriented data base, the flexibility could be improved. In this case, the capabilities for spatial analysis could be substantially improved by the integration of ModelBuilder™ into ESRI® ArcGIS.

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Sažetak

Razvoj višeatributnoga prostornoga sustava za pomoć pri odlučivanju kod odabira sustava pridobivanja drva

Cilj je ove studije bio razvoj prostornoga sustava koji bi pomogao pri odlučivanju (SDSS) u odabiru najpogodnijega načina pridobivanja drva uz procjenu ekoloških, ekonomskih i društvenih utjecaja na radove pri pridobivanju drva nakon poboljšanja šumske prometne infrastrukture i/ili nakon primjene novih postupaka sječe, izradbe i *transporta drva. Spomenuti je model razvijan u četiri ciklusa. Nakon definiranja područja primijenjena je tehnološka prosudba sustava pridobivanja drva s obzirom na lokalne čimbenike. Prikladni su sustavi zatim uspoređeni primjenom višeatributne teorije korisnosti (MAUT) zbog odabiranja najpogodnijega sustava pridobivanja drva. Sedam nezavisnih uvjeta i pokazatelja korišteno je pri odabiru: utjecaj na tlo (nosivost tla, kPa), potencijal globalnoga zagrijavanja (potrošnja goriva u kg ekvivalent ugljičnoga dioksida, kg CO_2), oštećenost sastojine (%), kontribucijska marža (€/m^3), vrijeme premještanja (zbroj tehnoloških pokazatelja, %), zaposlenost (potreba za radnom snagom, h/m^3) i sigurnost pri radu (broj nezgoda/m^3). Za prevođenje apsolutnih u usporedive vrijednosti korištene su lokalne sklonosne funkcije. Težinski faktori za obilježja uspostavljeni su uz pomoć upravitelja lokalnih šumarskih poduzeća. Analizom scenarija procijenjene su posljedice različitih zamjenskih postupaka pridobivanja drva.*

Model je ugrađen u geografski informacijski sustav (GIS) i predočen na primjeru šumarskoga poduzeća koje gospodari s 1100 hektara šuma na nagnutim terenima u Donjoj Austriji. Pri ocjeni određenih scenarija korištenje forvardera s vitlom imalo je pozitivan utjecaj na proizvodnost (+14 %), emisiju ugljičnoga dioksida (–2 %), oštećivanje sastojine (–7 %), kontribucijske marže (+15 %) i na ozljede radnika (–36 %). Općenito se može reći da primjena forvardera s vitlom ima više pozitivnih nego negativnih posljedica. Primijenjeni model sugerira izvoženje 56 % drva spomenutom tehnologijom i smanjenje primjene stupnih šumskih žičara s 90 na 38 %.

Za jednu drugu površinu veličine 11 hektara poboljšanje šumske prometne infrastrukture dalo je pozitivan utjecaj na proizvodnost (+50 %), potrošnju goriva (–14 %) i kontribucijsku maržu (+20 %), ali je ekonomski utjecaj bio prenizak za davanje preporuke za izgradnju šumske ceste. Samo je kombinacija povećanja gustoće šumskih cesta i primjena forvardera s vitlom dovela do pozitivnoga pomaka utrostručivanjem proizvodnosti, povećanjem graničnoga prihoda s 40 na 56 %, smanjenjem razine oštećenosti sastojine za 53 % i smanjenjem razine ozljeda za 93 %. Istodobno su se pogoršali utjecaj na podlogu (od 15 do 332 kPa) i zaposlenost (–82 %). Iznošenje drva stupnim šumskim žičarama u potpunosti je zamijenjeno izvoženjem drva forvarderom s vitlom. Taj primjer pokazuje potrebu uključivanja kako infrastrukture, tako i tehnologije za operativno planiranje pridobivanja drva.

Kao i svi višeatributni modeli korisnosti, ovaj pristup rezultira kardinalnim nizom svih inačica zamjenskih rješenja s obzirom na njihovu očekivanu korist. Kakogod, donositelj odluka mora biti svjestan da krajnje rješenje može biti samo kompromisno rješenje zasnovano na subjektivnoj racionalnosti. Analiza je osjetljivosti snažniji alat sustava za potporu pri odlučivanju. Ugrađivanje ovoga modela odlučivanja u GIS mora nadgledati iskusni korisnik. Korištenjem modela sustava upravljanja i pohranom sastavnica modela u objektno orijentiranu bazu podataka može se povećati fleksibilnost modela. U tom slučaju mogućnosti prostorne analize uvelike se mogu poboljšati primjenom alata ModelBuilder™ u računalnom programu ESRI® ArcGIS.

Provodi se daljnje usavršavanje opisanih postupaka, a model će se testirati na drugim istraživanim područjima, posebice na ravnim terenima, o čem zasad ne postoji dovoljno spoznaja. U budućnosti bi se mogla razmotriti i uporaba podataka LIDAR-a visoke razlučivosti. Za poboljšanje rezultata koristit će se još veći broj kriterija zadovoljavajuće kakvoće, a za postizanje bolje prilagođenosti korisniku usavršit će se korisničko sučelje i kontrola međudjelovanja korisnika i modela. Provjerit će se praktična primjenjivost ovoga modela pri planiranju šumskih cesta i dobavi energetskoga drva.

Ključne riječi: pridobivanje drva, mreža šumskih cesta, sustav za pomoć pri odlučivanju, procjena korisnosti

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