Development of a Multi-Criteria Decision Support Tool for Energy Wood Supply Management

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Abstract – Nacrtak

The use of wood for heat and energy production has increased over the last two decades and there is still increasing demand. Harvesting energy wood can provide an extra source of income for the forest owners and generally affects the economics of forest operation positively, but impacts on environmental and social aspects, like the ecological balance of the forest, working conditions and rate of employment, need to be accounted as well. Individual stakeholders are faced with a number of options regarding energy wood harvest and supply systems though they often only have limited knowledge about their impacts. It is also important to understand that individual stakeholders often have different preferences regarding the balance between economic, ecological and social impacts.

A computer-based decision support tool was developed in Microsoft Excel® using Visual Basic for Applications® to assist stakeholders in identifying the most suitable energy wood supply chain to meet their needs. The tool considers a number of criteria such as energy efficiency, nutrient balance, stability and vitality of the remaining stand and soil, contribution margin, supply guarantee, employment rate and working safety. Users can specify site, stand and environment data and technology parameters, and set their individual preferences for balance between the criteria. The overall utility of various treatment alternatives are calculated by an additive utility model and presented via on-screen graphs and tables.

The tool is designed to convey knowledge gained in research through practical and understandable tool. In addition to presenting the decision support tool, this paper explores the influence of criteria weighting, terrain conditions, transport distance and moisture content on selecting the most suitable supply chain.

Keywords: Decision support, utility model, supply management, energy wood, bioenergy harvesting, forest management planning, multiple-purpose forestry

1. Introduction – *Uvod*

The current contribution of wood fuels to the total energy production is already relatively high in some European countries. In the last two decades the demand for energy wood has been increasing and there is still potential to intensify utilization across Europe (Hall 1997; Moiseyev et al. 2011). The new directive (EU 2009) on renewable energy sources sets ambitious targets for all Member States. The EU should reach a 20% share of energy from renewable sources by 2020.

The development of renewable energy systems does not have a long history, which is the reason for a general lack of experience and understanding of renewable energy sources and technology – within the public sector as well as industry and among private users. The potential of energy wood in European Union countries is significant (Hall 1997; Berndes et al. 2003), but more has to be done to improve harvesting, transport and combustion technology. In addition to technology development, further improvements are needed regarding knowledge about bioenergy in general and forest fuels in particular (Kärhä 2011).

The conversion of forestry woody biomass into fuel and moving this resource from the forests to the plant is the challenge of any energy wood supply chain (EWSC), which consists of various processes, e.g. felling, extracting, chipping and transporting (Stampfer et al. 2011). There is also an ongoing discussion about ecological and social consequences of forest biomass harvesting, such as nutrient depletion of the soils, loss of biodiversity or working safety (Makeschin 1994; Bohlin and Roos 2002; Röser et al. 2006; Bright et al. 2010). The different players in the energy wood supply management (EWSM), e.g. forest managers have to take environmental, economic and social factors into account and aggregate them to insure a sustainable utilization. The directive on renewable energy (EU 2009) also requires national action plans for the development of renewable energy sources, and it establishes sustainability criteria for biofuels.

Due to the multitude of alternatives and objectives, choosing a supply chain approach is a complex task in EWSM. Given the challenge to choose the most suitable supply chain considering economic, environmental and social aspects, a decision support tool could be helpful. Multi Criteria Analysis (MCA) is one of many tools available to assist decision makers in the decision process. In recent years MCA has been extensively used for problem solving, primarily within the area of natural resource management. Most of these applications have been successful in developing applied management options leading to improved environmental and social management. A MCA approach enables investigators and decision makers to integrate the components of sustainable (social, economic and environmental) development (Hwang and Yoon 1981; Fath et al. 1999; Solomon and Hughey 2007).

Howard (1991) generally questioned the applicability of mathematical programming techniques for ill-structured problems, which are quite common in multiple-purpose forestry. Though well accepted in industry and business applications, MCA techniques as decision support tools have rarely been applied for the evaluation in forestry (e.g. Mendoza 1989; Canham 1990; Næsset 1997; Sheppard and Meitner 2005; Wolfslehner et al. 2005; Wolfslehner and Vacik 2008; Kangas et al. 2008). For European conditions, Kangas (1993); Kangas et al. (2001); Kangas and Kuusipalo (1993); Pukkala and Kangas (1993); Vacik and Lexer (2001); Lexer et al. (2005); Kühmaier and Stampfer (2010) provide examples of MC-solutions for multi-objective and multi-criteria decision problems including biodiversity and amenity values.

MCA tools for supporting decision making in EWSM are rare but, due to the increasing attention to sustainability in this area, they are becoming more important in recent years (Windisch et al. 2010). There have been several studies about estimating local energy wood fuel resources (e.g. Vainio et al. 2009; López-Rodríguez et al. 2009; Padari et al. 2009; Fernandes and Costa 2010; Gómez et al. 2010; Emer et al. 2011; Ranta and Korpinen 2011), cost analyses (e.g. Laitila 2006; Laitila et al. 2010; Tahvanainen and Anttila 2011) or optimizing supply networks (e.g. Ranta 2005; Kanzian et al. 2009; Kim et al. 2011). Nevertheless, there is still a lack of tools for comparing and evaluating EWSCs on a multi-criteria level and giving recommendations for the selection of the most suitable systems for a given condition and set of objectives.

The aim of this study is to develop a decision support tool for EWSM based on MCA that assesses sustainability including economic, environmental, and social criteria. A model was designed to evaluate alternatives and scenarios based on user defined site, stand, environment and machine data. The tool covers the current state-of-the-art energy wood supply chains and is implemented in a common spreadsheet platform.

2. Material and Methods – *Materijal i metode*

An essential step in developing a decision support system is the design of the framework, which includes defining the system to be modeled. The framework combines different aspects of DSS-development. The process model represents the flow of data and information throughout the 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 modeled system. Finally, the implementation model comprises software architecture and technical solutions to implement the master model (Lexer et al. 2005).

2.1 Framework – *Okosnica*

To ensure the quality of the consultation process, the user is guided through a standardized decision-making process (Fig. 1). To begin, the user is provided with a default scenario (based on average values from previous studies) or with an existing scenario from a previously saved session. The user is advised to follow the recommended menu starting with worksheet 1 (S1) and finishing with sheet 5 (S5). After identifying his/her individual preferences, the user initializes the

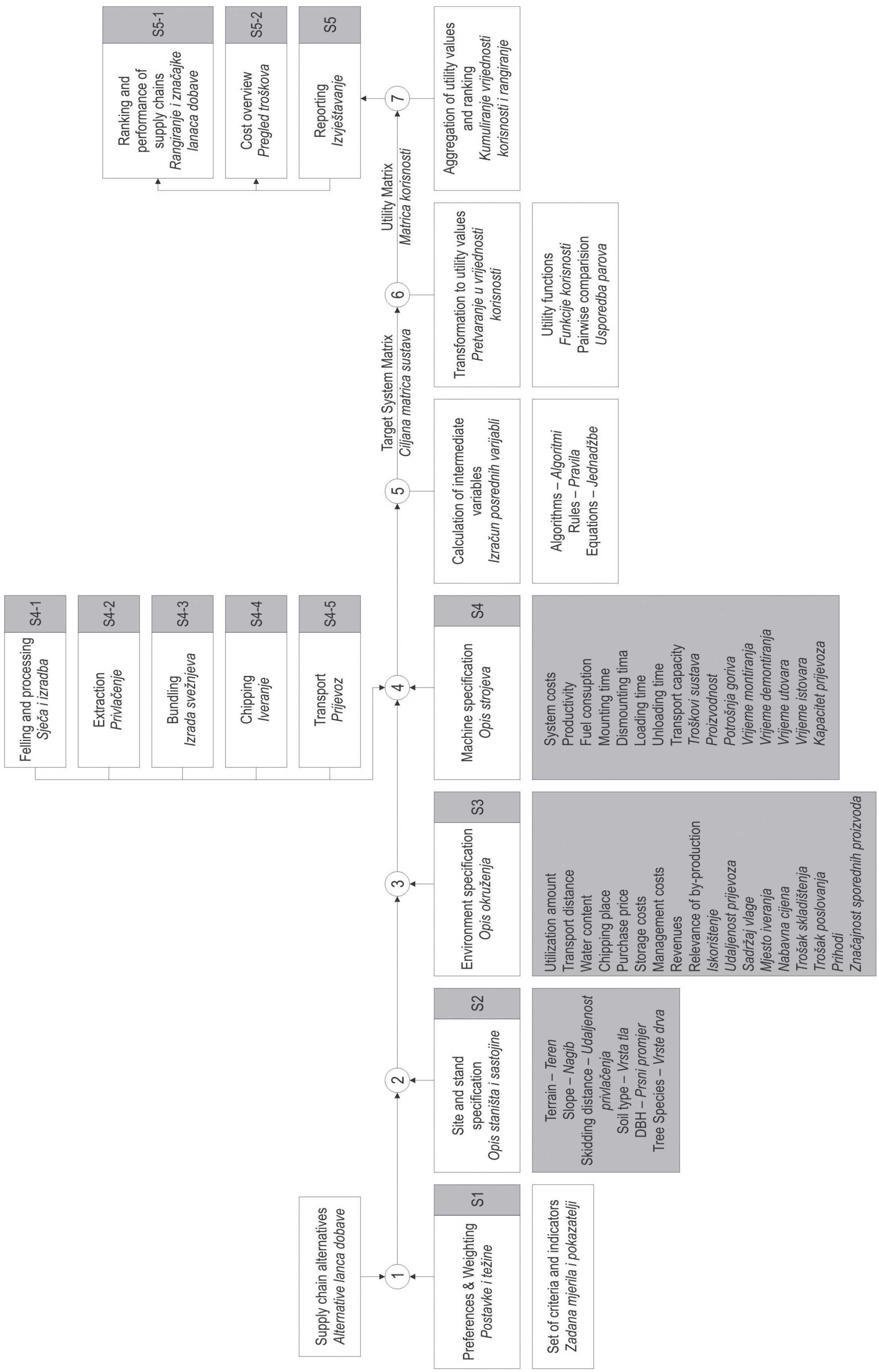

Fig. 1 Framework of the decision support tool for energy wood supply management
Slika 1. *Okvir alata za pomoć pri odlučivanju za upravljanje dobavom energijskoga drva*

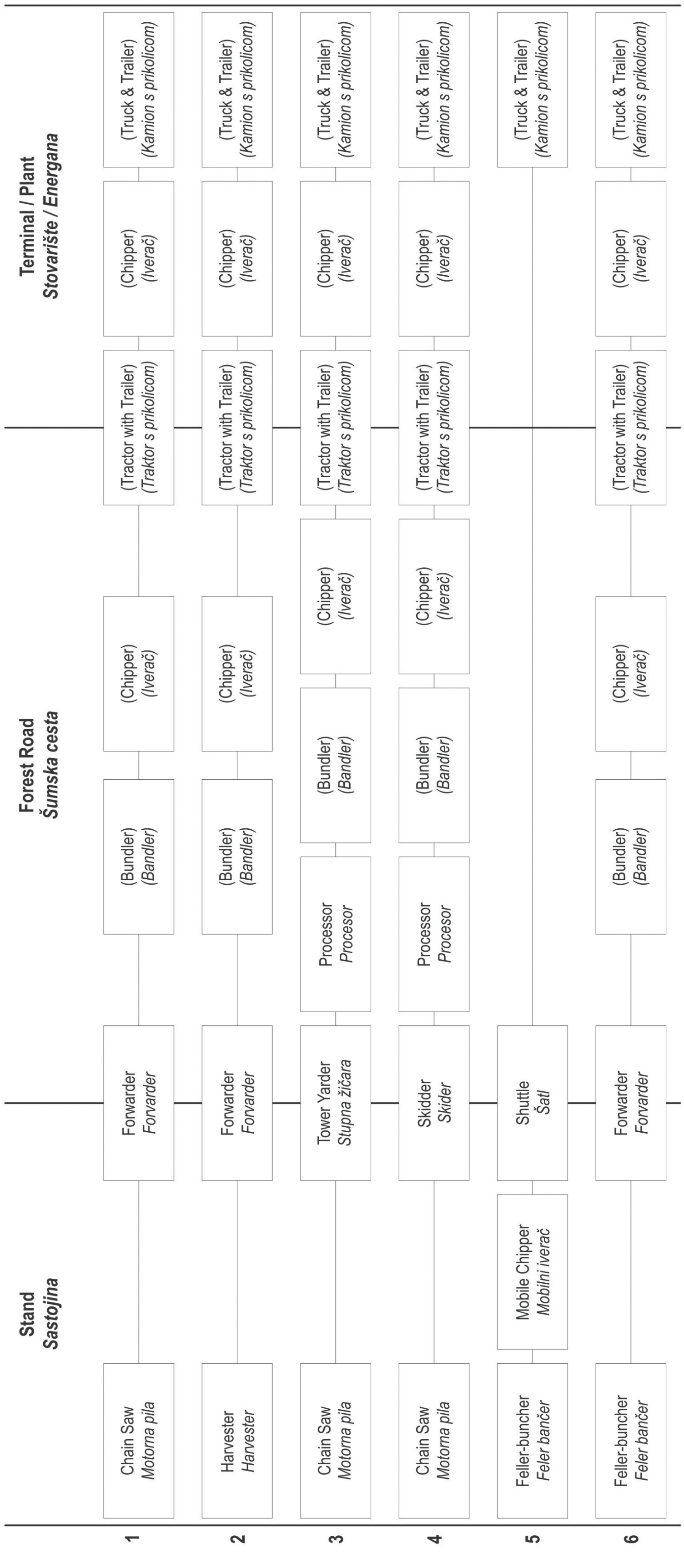

Fig. 2 State-of-the-art energy wood supply chains
Slika 2. *Najsuvremeniji lanci dobave energijskoga drva*

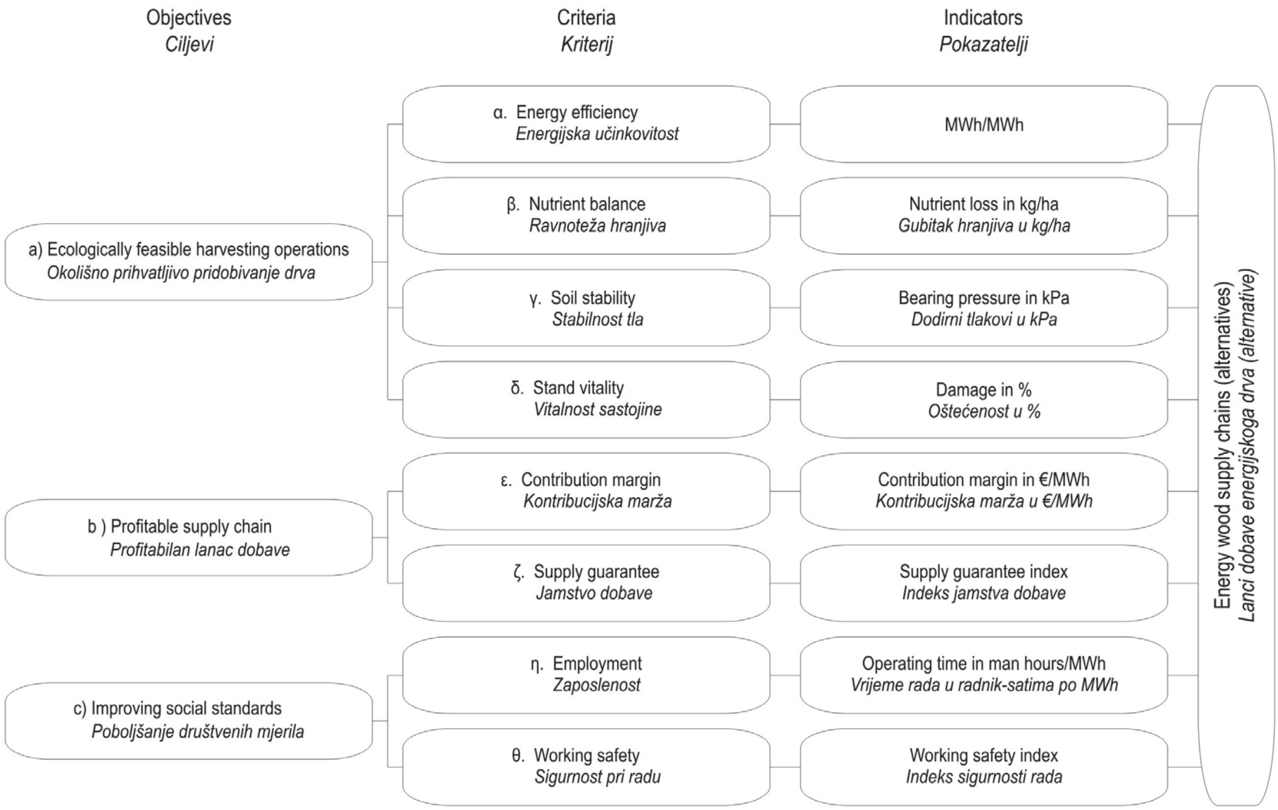

Fig. 3 Objectives, criteria and indicators in energy wood supply management
Slika 3. *Ciljevi, kriteriji i pokazatelji pri upravljanju lancem dobave energijskoga drva*

planning process for a particular forest by classifying the current stand, site and environmental conditions. Harvesting and transportation data is the last input made by the user. All the input data (grey colored in Fig. 1) will be transferred into utility values after executing several intermediate calculations (utility analysis). By aggregating these values and ranking the results the most suitable EWSC will be determined. The model provides the decision maker with tables and figures that summarize the suggestions of the model.

2.2 Process and formal model – *Postupak i zadani model*

Energy wood supply chains (alternatives)

In estimating the most suitable EWSC, the DS tool consists of 48 alternatives within 6 supply groups (Fig. 2). The alternatives vary in terms of harvesting and transporting machines used, harvesting methods (whole tree, tree length, cut-to-length), chipping location (stand, forest road, terminal, plant), and the type of woody biomass harvested (whole trees, harvesting residues, or both). Bundling is an optional process for compressing harvesting residues. Biomass can be transported as forest residues, round-wood, pressed bundles or chips (Hakkila 2004; Stampfer and Kanzian 2006; Kühmaier et al. 2007; Kärhä 2011; Stampfer et al. 2011).

Selection and weighting of criteria and indicators

For the evaluation process, independent criteria and indicators (C&I) have been chosen. C&I-approaches appear to be effective in measuring aspects of sustainable forest management (Prabhu et al. 1999; Wolfslehner et al. 2005). For this tool, 6 indicators were defined with quantitative values – nutrient loss, bearing pressure, energy-efficiency, damage on remaining stand, contribution margin and operating time – and 2 index values – supply guarantee and working safety (Fig. 3).

In a database (target system matrix), indicator values were assigned to each alternative. The data matrix describes how good the particular criterion fulfills the respective alternative. The user indicates his/her preferences by weighting (S1 in Fig. 1) pre-defined criteria. If one of these criteria does not fit within the scope of

Table 1 Limits for the technological evaluation of energy wood supply chains
Tablica 1. *Ograničenja pri tehnološkom vrednovanju lanaca dobave energijskoga drva*

Criteria – *Kriteriji*	Classes – *Razredi*
Morphology – *Reljef*	uniform – *ujednačen*, non-uniform – *neujednačen*
Soil strength – *Nosivost podloge*	high – *zadovoljavajuća*, low – *nezadovoljavajuća*
Slope – *Nagib*	<35%, 35–60%, >60%
DBH – *Prsni promjer stabala*	<25 cm, <50 cm, >50 cm
Extraction distance – *Udaljenost privlačenja*	<80 m, 80–800 m, >800 m
Soil type – *Vrsta tla*	non-sensitive, sensitive (soil depth <30 cm, virgin soil, podzol, rendzina, terra fusca, moor) *neosjetljiva, osjetljiva (dubina tla <30 cm, podzol, renzina, smeđa tla, treset)*
Chipping place – *Mjesto iveranja*	stand – *sastojina*, forest road – *šumska cesta*, terminal – *stovarište*, plant – *energana*

objectives, the user may give a weight of zero. The proportions of the weights are calculated in percentage values to generate a total of 1.

Specification

For the technological evaluation, an algorithm, similar to a decision tree, filters feasible alternatives. A decision tree (Magee 1964) is a decision support tool that uses a tree-like graph or model of decisions and their possible consequences. 7 criteria with predefined limits have been used to exclude not applicable alternatives within the evaluation process (Table 1).

Site and stand specification (S2 in Fig. 1) acts as input data for the decision tree. The slope 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-operated machines, e. g. tower yarders (800 m) and skidders (80 m). The limiting diameter at breast height (DBH) for feller-buncher, harvester and processor depends on the type of harvesting head. A strongly varying morphology and low soil strength are restricting factors for ground-based systems as a result of reduced trafficability (Kühmaier and Stampfer 2010).The utilization of forest residues can result in ecological risks (Krapfenbauer 1983) as well as in growth reduction (Sterba 2003), as valuable nutrients are removed from the forest. Therefore, the utilization of residues is only recommended for nutrient-rich soil conditions. Hence the whole-tree (WT) method should be excluded on sensitive soils.

The performances of indicator values vary not only according to site and stand data, but also to according to environment and machine specifications (S3 and S4 in Fig. 1). Chipping place, transport distance and moisture content, for example, play a decisive role for the efficiency of the whole EWSC. The main characteristics of the harvesting processes in the supply chain are specified with productivity, system costs and fuel consumption. Default Input values were taken from energy wood harvesting/supply studies (e.g. Kühmaier et al. 2007; Stampfer et al. 2011). Furthermore, productivity models are implemented in the DSS to help the user estimate the productivity of the various processes.

The specification data is also used to calculate indicator values for energy efficiency, contribution to margin and employment rate. The indicator values for all other criteria are fixed for each alternative and therefore unchangeable. All the indicator values (target system matrix) act as input for the utility analysis.

Transformation of target values into utility values

To evaluate the overall utility of alternatives, for cases where more than one solution is possible, an approach borrowed from multiple-attribute utility theory (MAUT) was adopted (Goicoechea et al. 1982). It is assumed that there are a certain number of criteria and a one-dimensional utility function for each of these criteria (Kühmaier and Stampfer 2010).

In case of quantitative indicators, such as with the amount of € per MWh as indicator for contribution to margin, quantitative utility functions were estimated and used to transfer an indicator from its measurement scale to the dimensionless »utility« scale on the interval [0–1]. In this study, for all quantitative data, the utility functions have been scaled with score range procedure on an interval scale (Kangas et al. 2008). Interval scale can be interpreted as local scale; the length of the interval depends on specific planning situation (Kainulainen et al. 2007).

In cases where no quantitative values for the indicators can be provided to measure the progress towards objectives, alternatives were directly compared in pairwise comparisons employing Saaty's ratio-scale approach and expert judgment (Saaty 1977). All pairwise comparisons were performed by experts. Similar approaches to synthesize preference information across multiple attributes were described in Vacik and Lexer (2001) and Lexer et al. (2005). The resulting utility values were normalized and stored in a database (utility matrix).

Aggregation

Aggregation of utility values is necessary to describe the overall utility of alternatives. This aggregation is done by criteria weighting within 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 most suitable alternative is the one with the highest overall utility (Kühmaier and Stampfer 2010).The most applied multi-attribute utility function is the linear additive utility function written as

$$U = a \times (\alpha \times U_{EE} + \beta \times U_{NB} + \gamma \times U_{SS} + \delta \times U_{SV}) + b \times (\varepsilon \times U_{CM} + \zeta \times U_{SG}) + c \times (\eta \times U_{FM} + \theta \times U_{WS}) \quad (1)$$

under the constraints that weighting coefficients $a + b + c = 1$, $\alpha + \beta + \gamma + \delta = 1$, $\varepsilon + \zeta = 1$ and $\eta + \theta = 1$. The objectives and criteria corresponding to the weighting coefficients a, b, c and α, β, γ, δ, ε, ζ, η, θ are presented in Fig. 3. U_{EE}, U_{NB}, U_{SS}, U_{SV}, U_{CM}, U_{SG}, U_{EM} and U_{WS} are the utility values for the criteria energy efficiency, nutrient balance, soil stability, stand vitality, contribution margin, supply guarantee, employment and working safety.

Report

The results of the calculation are available in anon screen report. The report displays the most suitable EWSC within each EWSC group and a ranking of these groups. The overall utility is visible both as a value and as a graph. In this way it is possible to see differences at a glance. As additional information, the absolute values of the indicators are displayed. This helps the user to get a better understanding of the impacts when using certain EWSCs. Another sheet shows the supply costs subdivided into several processes available as €/loose m³, €/MWh, €/solid m³, and €/dry tons. This information is also available as a chart. Finally the supply costs of energy wood is compared with other fuels, like natural gas, heating oil, black coal, wood briquettes, pellets, and firewood.

2.3 Implementation – *Primjena*

The program was constructed in Microsoft Excel® using Visual Basic for Applications® technology (VBA). VBA offers a sophisticated programming tool, which facilitates the creation of applications with user interfaces and custom dialog boxes. By generating buttons, the user is guided more easily through the system. This user guidance is organized in a starting page with general information about the tool and links to several worksheets and sub-sheets. To execute the tool, a first time user is instructed to follow the intended sequence (S1–S5 in Fig. 1). There is always one active sheet visible. If the user clicks on a button. the inactive sheet will be hidden and the new active sheet will be visible. To assist the user, some simple calculating sheets can be opened and closed for specific processes, e.g. for calculating productivity or showing details within the EWSC groups. Additional directions on entering specification data are available through comments if the user clicks on particular terms.

The weights of each criterion are defined by the user. With the interactive interface, the user sees immediately how the current set of weights affects his preferences. The user can enter or change specification data (grey-covered boxes in Fig. 1) and save input data and results. However, in the input fields, default values are given, compiled from previous studies, so that entering data is not mandatory to make the tool work. The calculation of intermediate values, the target system and the utility matrix as well as the ranking of the alternatives are in the background and are not visible to the user. The applicant may store the scenario (including all parameter settings) at any time, print the report, exit the scenario session or return to the beginning.

3. System demonstration – *Prikaz sustava*

Since the model has a wide range of scenarios with 115 potential input fields, for the purpose of this demonstration, variations were limited to changes in weighting as well as in slope, transport distance and moisture content. The remaining specification data (Annex: Table A1 and A2) is constant for all scenarios. For all other input fields no technological restrictions were used.

3.1 Weighting scenarios – *Scenariji težina*

In the first example the weighting of the economic criteria was changed and the performance of supply groups 2, 3, 5 and 6 was analyzed (Fig. 4). Group 2 (harvester-forwarder) was always the most suitable EWSC. Group 3 (chain saw-tower yarder) is most similar to group 6 (feller buncher-forwarder), but if the importance of economics is increasing the group 3 has an advantage because the supply costs are lower, especially for felling and extracting (by-production).

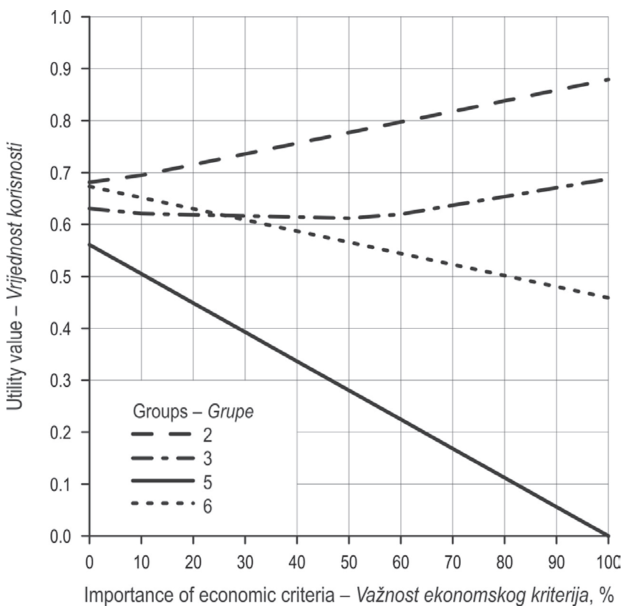

Fig. 4 Most suitable EWSCs according to the importance of economic criteria

Slika 4. *Najpogodniji lanci dobave energijskoga drva s obzirom na privrednu važnost*

Furthermore chipping and storage of logs and residues (group 6) is more expensive than processing logs (group 3). Group 5 (feller buncher-chipper-shuttle) is not recommended for energy wood supply, as the supply costs, especially for chipping in the stand, are too high.

Group 5 and 6 have a negative contribution margin (–7.89 € and –7.03 €, respectively). If no economic criteria are considered, there is little difference (spread of 0.12) between the supply chains, but this will change dramatically as the economic criteria weighting increases to 50% (0.50) or 100% (0.88). This clearly shows that economic considerations most highly affect the difference between supply chains and have a greater influence on EWSC choice than ecological and social criteria that are very similar between the system options. From an ecological point of view all EWSCs are similar with the exception of group 5, which is the only poor one. The harvester and forwarder system is evaluated as one of the best alternatives from an economic, ecological and social point of view.

Example 2 shows an analysis of EWSCs in flat (<30%) versus steep terrain (>60%) with the weightings described in Table 2. Eight scenarios have been compared in this example.

In flat terrain, all EWSCs are technically applicable so 48 alternatives are available to the decision support tool. Under these circumstances, where the decision process is complex, the tool provides the greatest value. In the balanced scenario, group 2 has been selected as the most suitable supply chain with a 3.94 €/m^3 loose contribution margin and a primary energy consumption of 1.63%. Group 3 is recommended in the ecological weighted scenario mainly due to the absence of bearing pressure with tower yarder extraction. The economic weighted scenario delivers the same result as the balanced scenario. From a social aspect, group 2 is also the most suitable but only where forest residues, extracted separately by a forwarder, are used as energy wood. Therefore, the productivity of the EWSC is very low but offers a high rate of employment (0.24 hours/m^3 loose). Emissions and energy consumption are also very high for this scenario and there is a negative contribution margin. In this case it

Table 2 Weighting scenarios

Tablica 2. *Scenariji (težinskoga) vrednovanja*

Criteria *Kriterij*	Balanced *Uravnotežen*	Economic *Privredni*	Ecological *Okolišni*	Social *Socijalni*
Energy efficiency – *Energetska djelotvornost*	8%	5%	15%	5%
Nutrient balance – *Ravnoteža hraniva*	8%	5%	15%	5%
Soil stability – *Stabilnost tla*	8%	5%	15%	5%
Stand vitality – *Vitalnost sastojina*	8%	5%	15%	5%
Contribution margin – *Kontribucijska marža*	17%	30%	10%	10%
Supply guarantee – *Jamstvo dobave*	17%	30%	10%	10%
Employment – *Zaposlenost*	17%	10%	10%	30%
Working safety – *Sigurnost pri radu*	17%	10%	10%	30%

Table 3 Most suitable energy wood supply chains on flat terrain
Tablica 3. *Najpogodniji lanci dobave drva na ravnome terenu*

Flat terrain ***Ravan teren***	Balanced *Uravnotežen*	Ecological *Okolišni*	Economic *Privredni*	Social *Socijalni*
Most suitable supply group *Najpogodnije grupe dobave*	Group 2 *Grupa 2*	Group 3 *Grupa 3*	Group 2 *Grupa 2*	Group 2 *Grupa 2*
Most suitable supply chain *Najpogodniji lanac dobave*	Felling and processing with harvester, extracting with forwarder (logs), transportation of logs, chipping at plant *Sječa i izradba drva harvesterom, izvoženje forvarderom (trupci), prijevoz trupaca, iveranje kod energane*	Felling with chain saw, extracting with tower yarder (tree), processing with processor, transportation of residues, chipping at plant *Sječa motornom pilom, iznošenje stabala stupnom žičarom, izradba drva procesorom, prijevoz šumskoga ostatka, iveranje kod energane*	Felling and processing with harvester, extracting with forwarder (logs), transportation of logs, chipping at plant *Sječa i izradba drva harvesterom, izvoženje forvarderom (trupci), prijevoz trupaca, iveranje kod energane*	Felling and processing with harvester, extracting with forwarder, transportation of residues, chipping at plant *Sječa i izradba drva harvesterom, izvoženje forvarderom, prijevoz šumskoga ostatka, iveranje kod energane*
Nutrient loss – *Gubitak hraniva*, kg/ha	640	960	640	960
Bearing pressure – *Dodirni tlak*, kPa	300	10	300	300
Emissions – *Polucije*, kg CO_2/m^3 loose	3.15	3.51	3.15	7.31
Energy consumption – *Potrošnja energije*, kWh/m^3 loose	12	14	12	29
Energy efficiency – *Energetska učinkovitost*, %	1.63%	1.82%	1.63%	3.78%
Damage on stand – *Oštećenost sastojine*, %	11%	3%	11%	5%
Contribution margin – *Kontribucijska marža*, €/m^3 loose	3.94	2.67	3.94	–11.42
Working hours – *Norma vremena*, h/m^3 loose	0.10	0.12	0.10	0.24

is readily identifiable that too strong a focus on social criteria can have negative impact on ecology and economics. The trade-offs of a multi-criteria evaluation are clearly distinguishable (Table 3). Harvesting will be carried out as a by-production in the ecological scenario. In this case only residues will be used as fuel wood. The logs are delivered to saw and paper mills. The impacts (indicators) for all by-production processes are valued at 10%. This quota correlates approximately to the ratio of revenues for energy wood versus logs. Based on this ratio, the impacts of some indicators are reduced, e.g. damage to remaining stand is denoted with only 3% in contrast to real damage of 29%.

In steep terrain, the option of wheeled or tracked vehicles is eliminated, so only harvesting operations with a tower yarder (group 3) are possible. In the balanced scenario, the processing is done by a processor at the roadside and only the logs are transported to the plant, where they are stored and chipped. This scenario has an energy efficiency of 1.97% and a contribution margin of –4.57 €/m³ loose. From an ecological point of view, the same EWSC as in flat terrain should be used. Harvesting will be carried out as by-production for the ecological and economic scenario. The social scenario suggests using logs and residues for energy production. This result has once again a negative contribution margin but the rate of employment is boosted to 0.37 hours/m³ loose (Table 4).

3.2 Sensitivity analysis – *Analiza osjetljivosti*

The following sensitivity analysis shows the impacts on energy demand and the contribution margin as it relates to transport distance and moisture content.

A longer transport distance increases transport time and therefore costs, which results in a lower con-

Table 4 Most suitable energy wood supply chains on steep terrain
Tablica 4. *Najpogodniji lanci dobave drva na strmom terenu*

Steep terrain *Strmi teren*	Balanced *Uravnotežen*	Ecological *Okolišni*	Economic *Privredni*	Social *Socijalni*
Most suitable supply group *Najpogodnije grupe dobave*	Group 3 *Grupa 3*	Group 3 *Grupa 3*	Group 3 *Grupa 3*	Group 3 *Grupa 3*
Most suitable supply chain *Najpogodniji lanac dobave*	Felling with chain saw, extracting with tower yarder (tree), processing with processor, transportation of logs, chipping at plant *Sječa motornom pilom, iznošenje stabala stupnom žičarom, izradba drva procesorom, prijevoz trupaca, iveranje kod energane*	Felling with chain saw, extracting with tower yarder (tree), processing with processor, transportation of residues, chipping at plant *Sječa motornom pilom, iznošenje stabala stupnom žičarom, izradba drva procesorom, prijevoz šumskoga ostatka, iveranje kod energane*	Felling with chain saw, extracting with tower yarder (tree), processing with processor, transportation of residues, chipping at plant *Sječa motornom pilom, iznošenje stabala stupnom žičarom, izradba drva procesorom, prijevoz šumskoga ostatka, iveranje kod energane*	Felling with chain saw, extracting with tower yarder (tree), processing with processor, transportation of logs & residues, chipping at plant *Sječa motornom pilom, iznošenje stabala stupnom žičarom, izradba drva procesorom, prijevoz trupaca i šumskog ostatka, iveranje kod energane*
Nutrient loss – *Gubitak hraniva*, kg/ha	640	960	960	960
Bearing pressure – *Dodirni tlak*, kPa	10	10	10	10
Emissions – *Polucije*, kg CO_2/m^3 loose	3.72	3.51	3.51	5.10
Energy consumption – *Potrošnja energije*, kWh/m^3 loose	15	14	14	20
Energy efficiency – *Energetska učinkovitost*, %	1.97%	1.82%	1.82%	2.67%
Damage on stand – *Oštećenost sastojine*, %	29%	3%	3%	29%
Contribution margin – *Kontribucijska marža*, €/m^3 loose	–4.57	2.67	2.67	–7.98
Working hours – *Norma vremena*, h/m^3 loose	0.34	0.12	0.12	0.37

tribution margin (Fig. 5). Group 3, 5 and 6 have a negative contribution margin even at short distances of approximately –5.8 €/m^3 loose due to high harvesting costs. The contribution margin will further decrease to –6.8 €/m^3 loose and –8.1 €/m^3 loose for distances of 50 and 100 km, respectively. Only group 2 has positive results for short, medium and long distances of 4.8, 3.6 and 2.1 €/m^3 loose because the use of logs as energy wood results in lower felling, extracting and chipping costs. Only distances of more than 170 km will generate negative results.

Longer transport distances require more fuel and therefore a higher energy demand. For a distance of 10 km, EWSCs have an energy demand between 1.4 and 3.3% in relation to the energy content of the wood. Increasing the transport distance to 100 km causes an increase in energy demand of about 0.8 percentage points (Fig. 5). For group 2 and 5, the energy demand is almost uniformly distributed among individual processes. The extraction with tower yarder in group 3 requires 50% of the entire energy demand due to low productivity (8.5 m^3/h) and high fuel consumption (16 l/h). The low productivity (17 m^3 loose/h) of the mobile chipper explains the huge energy demand for chipping in group 5 (Table 5).

For a transport distance of 38 km, the reduction of the moisture content from 50 to 30% results in an increase in contribution margin ranging between 0.8 and

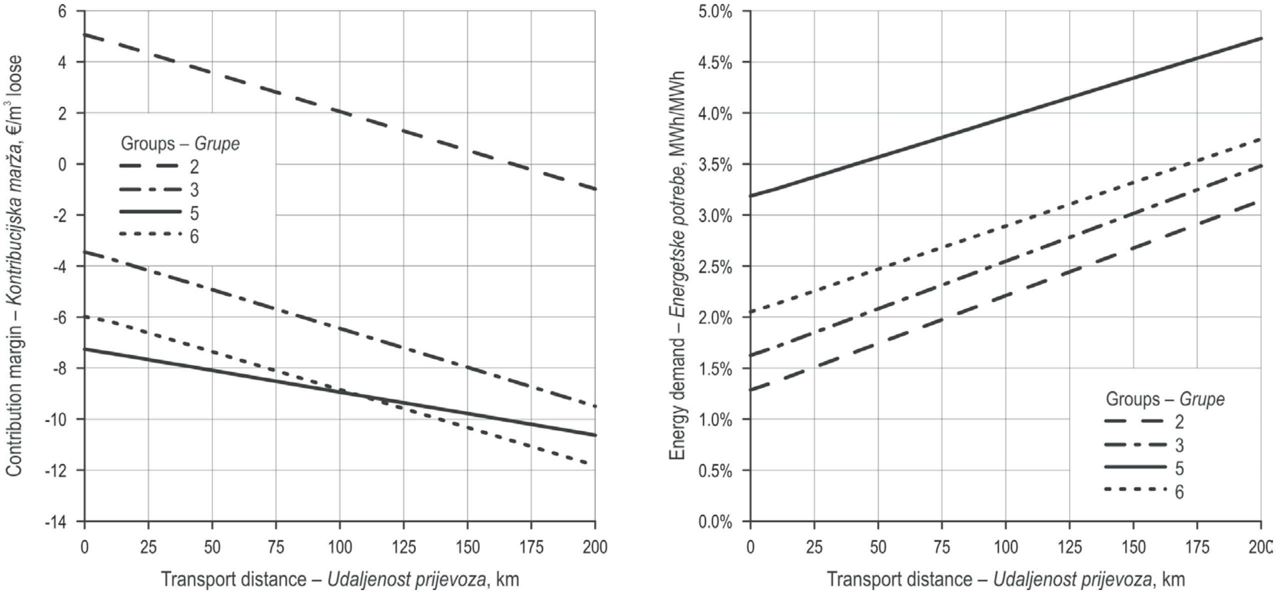

Fig. 5 Performance of EWSC as a function of transport distance
Slika 5. *Značajke lanaca dobave energijskoga drva u ovisnosti o udaljenosti prijevoza*

Table 5 Energy demand for energy wood supply processes
Tablica 5. *Energetske potrebe postupaka dobave energijskoga drva*

Process – *Postupak*	Group 2 – *Grupa 2*	Group 3 – *Grupa 3*	Group 5 – *Grupa 5*	Group 6 – *Grupa 6*
Felling, delimbing – *Sječa, kresanje grana*	27%	8%	17%	23%
Extracting – *Privlačenje drva*	22%	50%	9%	30%
Chipping – *Iveranje*	24%	20%	63%	25%
Transportation – *Prijevoz*	27%	22%	11%	22%
kWh/m^3 loose	13	16	27	18

1.6 €/m^3 loose and a reduction in energy demand ranging between 0.13 and 0.19 percent points (Fig. 6). Lower moisture content reduces the unit weight, which decreases fuel consumption and allows the transport of more wood (energy) per load. The impact is greater with logs than residues since residues have a much lower density.

4. Discussion – *Rasprava*

This paper presents the development of a Multiple Criteria Decision Support Tool for EWSM, its implementation as an easy-to-use software and the demonstration of its use through scenario analysis. The tool focuses on state-of-the-art energy wood supply chains covering felling through transportation to the plant and evaluates alternative systems based on ecological, economic and social criteria.

Several papers (e.g. Spinelli et al. 2007; Cremer and Velazquez-Marti 2007; Jylhä and Laitila 2008; Ovaskaenen et al. 2008; Rottensteiner et al. 2008; Lehtimäki and Nurmi 2011) explore case studies of energy wood harvesting systems with focus on a specific machine mix, terrain condition, stand type and environmental requirements. These single studies allow for an effective efficiency assessment of that particular system but, do not allow for easy comparisons with other supply chains. Other studies explore more than one EWSC but tend to focus only on certain processes within the supply chain, e.g. harvesting or transportation (Johansson et al. 2006; Kanzian et al. 2009; Tahvanainen and Anttila 2011). Further projects consider the type of woody biomass (Röser et al. 2006), or aim to optimize the supply network and allocation of material flows (Kanzian et al. 2009; Vainio et al. 2009). Criteria used in the evaluation of supply systems are gener-

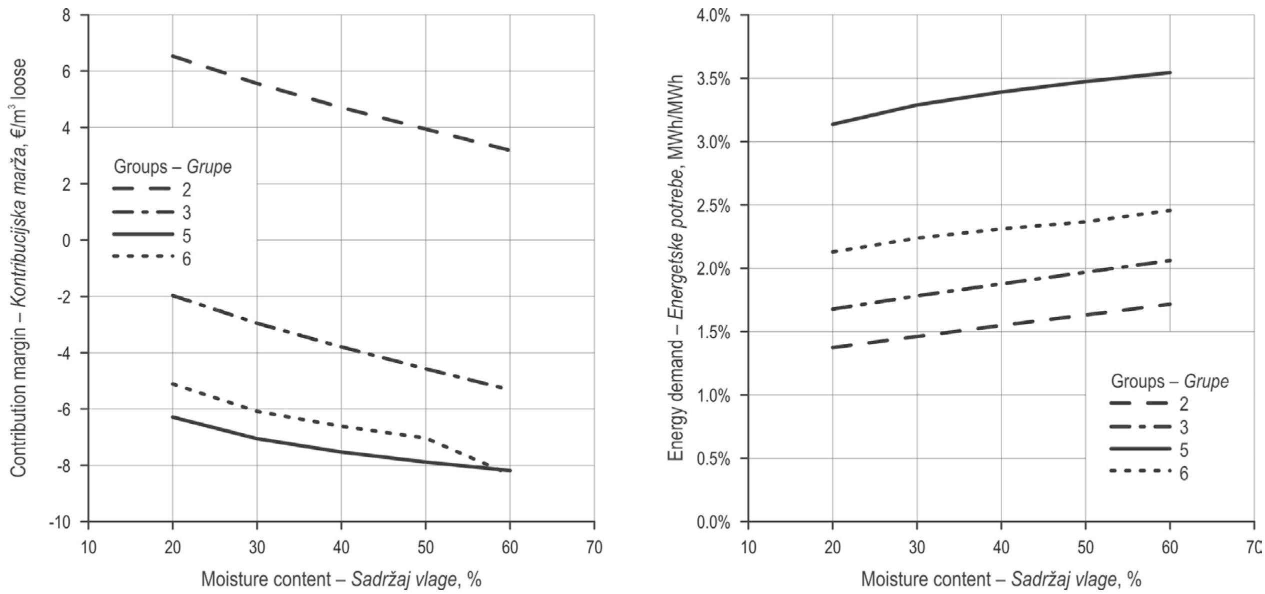

Fig. 6 Performance of EWSC as a function of moisture content
Slika 6. *Značajke lanaca dobave energijskoga drva u ovisnosti o sadržaju vlage*

ally limited to costs (Laitila 2006; Heikkilä et al. 2006; Laitila 2008; Röser et al. 2011) and in some cases CO2 emissions (Alam et al. 2011). Even with the wealth of knowledge generated in recent years on EWSCs, there still has not been an application developed to meet the need for an approach to easily and effectively evaluate EWSCs based on all the important sustainability criteria. By using a multi-criteria approach, this tool represents an innovative approach to evaluate state-of-the-art EWSCs based on economic, environmental and social criteria.

A multi criteria decision support approach creates a good starting point for the practical application of sustainable EWSCs, where various dimensions of sustainability are integrated (Kangas et al. 2008). Economic targets are important for forest owners, but with increased emphasis on environmental, ecological and social outcomes in forestry, it has become increasingly important to optimize these outcomes in balance with economics. The proposed method attempts to include all the priorities of various parties (i.e. forest managers, harvesting companies, funding agencies) to ensure an integrated and holistic evaluation.

The tool is flexible in allowing users to define their priorities through individual criteria weighting. Where stakeholders do not wish to, or cannot, assign weights, the system uses a default assumption of equal weighting for ecological, economic and social criteria. The default allocation of weights prevents decision makers from exhibiting a preference for a policy option, as the allocated weights are common to all the policy options that are to be considered in later process steps. Despite this implication it is clear that the weighting exercise is sensitive to the expressed differences of those involved in the policy making process. Nevertheless, the explicit process through which this weighting occurs is expected to limit the strategic and politically motivated behavior that might occur at this and later stages, where similar issues might arise (Solomon and Hughey 2007). Some users, especially if they are inexperienced, may also have problems to set their preferences. If so, a fixed weighting matrix, developed by experts, individually or in group decision (Laukkanen et al. 2005), would be an alternative. In this case the worksheet S1 would not be active. Additionally, to include several stakeholder groups (e.g. supply chain managers, biodiversity protection managers, hunters, recreationists), distinct weighting matrices could be created for each group according to their objectives.

The tool provides a consistent approach to filter alternatives that are ecologically or technically feasible. Like all deterministic models, it cannot account for the effects of the randomness, but provides the possibility to assess the most common scenarios. The model represents the current situation and assessments of future scenarios require a forecast by the user. An implementation of methods to predict future conditions, e.g. a growth simulator, would be possible (Lexer et al. 2005) but was seen to add too much complexity in this case.

The use of indicators present a potential issue with accuracy so it is important (i) to select indicators that are appropriate for the purpose in question, and (ii) to establish a common understanding regarding the meaning of an indicator between the system developer and end-user, who finally must communicate the results to their client (Lexer et al. 2005). Indicators can only be used if they are available for each alternative. The quality and data availability depends often on the experience of the user (for input fields) and on information from previous studies and research projects. In our case, the data quality was sufficient for most of the indicators. For some indicators, additional differentiation would enhance the quality of the technological evaluation and the calculation of overall utility. The impact of nutrient loss was evaluated according to harvesting method and type of biomass used but could be improved by including tree species and utilization type (e.g. thinning, final cut). Similarly for the bearing pressure, including slope conditions, geology, soil type, and morphology with respect to damage related to harvesting method, machine type and experience of the operator, would improve the tool assessment. Finally, safety assessment could be improved by including machine type and the operator experience. With these opportunities in mind, increasing the amount and quality of data to run the tool, will also increase the effort to run the tool as well as the complexity of calculations and analysis.

As already mentioned in the weighting process, estimating specification data can be a challenge for the user. To reduce the effort, some specification data was fixed and is not visible to the user. For all other input fields, default values were used from previous research projects and studies. These default values are primarily from Austria, i.e. mountainous conditions.

The demonstration example shows that the tool is capable of generating consistent and feasible results in a complex multi-dimensional decision space. The final proof of acceptance of the tool will be provided by end-user adoption. Early feedback has been encouraging, indicating that most steps in the process are intuitive. Editing of customized parameter data sets, as well as printing of reports, are easy and do not require specialized computer knowledge since the tool is implemented within well-known software. To address tool specific issues, each worksheet and input field have user help notes.

Based on the results of the system demonstration and of running additional scenarios not included in this report, the following conclusions could be derived for balanced scenarios:

⇒ Fully mechanized systems should be preferred over highly, partly or non-mechanized systems.

⇒ Felling and processing with harvester achieves a higher utility value than doing this work with a chainsaw.

⇒ The method of extracting energy wood showed no significant differences. Only the value for skidding was slightly lower.

⇒ The cut-to-length method and the tree-length-method were more suitable than the whole tree method.

⇒ The utilization of whole trees or logs should be preferred over the supply of forest residues.

⇒ The supply and chipping of energy wood at the terminal or at the plant gained better results than chipping on the forest road.

⇒ Chipping in the stand and bundling are not recommended because of low productivity.

This was the first time a multi-criteria approach was used in decision support for complex EWSM decisions. The implemented supply chains should be continuously checked and updated, and if some new systems were established they should be added into the tool. The significance of C&I will be examined and if necessary completed with further C&I. Nevertheless, the goal should be to get a higher differentiation and more detailed results without making it more complex for the user. Kühmaier and Stampfer (2010) developed a SDSS for timber harvesting systems based on GIS. To include spatial level in EWSM, SDSS should be combined with the algorithms and calculations from the present tool as a goal for future research.

Acknowledgments – *Zahvala*

The authors would like to thank Austrian Research Promotion Agency (FFG) and Climate and Energy Fund for funding this research project. We would also like to thank Mark Brown of the University of the Sunshine Coast for editing and feedback on the manuscript and the tool.

For testing purpose the DS tool can be requested under office915@boku.ac.at.

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6. Annex – *Dodatak*

Specification data for system demonstration:

Table A1 Site, stand and environment specification
Tablica A1. *Stanišne, sastojinske i okolišne pojedinosti*

Parameter – *Parametar*	Specification – *Specifikacija*
Tree species – *Vrsta drva*	75% Spruce, 20% Beech, 5% Ash *75 % smreka, 20 % bukva, 5 % jasen*
Average DBH – *Srednji prsni promjer*	15 cm
Amount of utilization – *Iskorištenost pri sječi*	280 m^3
Transport distance – *Udaljenost prijevoza*	38 km
Moisture content (fresh) – *Sadržaj vlage (svježe)*	50%
Moisture content (dry) – *Sadržaj vlage (suho)*	30%
Storage costs at terminal – *Trošak skladištenja na stovarištu*	3 €/m^3
Storage costs at plant – *Trošak skladištenja kod energane*	1 €/m^3
Relevance in case of joint production – *Važnost u slučaju vezane proizvodnje*	10%
Purchase price – *Nabavna cijena*	1.5 €/m^3
Overhead costs – *Opći troškovi*	4%
Revenues – *Prihodi*	20 €/MWh

Table A2 Machine specification
Tablica A2. *Podaci o strojevima*

Process *Postupci*	Fuel consumption *Potrošnja goriva*	System costs *Trošak sustava*	Productivity *Proizvodnost*
Felling with chainsaw – *Sječa stabla motornom pilom*	0.53 l/h	33.5 €/h	3.0 m^3/h
Felling and delimbing with chainsaw – *Sječa stabla i kresanje grana motornom pilom*	0.53 l/h	33.5 €/h	2.0 m^3/h
Felling and processing with chainsaw – *Sječa i izradba drva*	0.53 l/h	33.5 €/h	1.5 m^3/h
Felling with feller-buncher – *Sječa feler bančerom*	6.5 l/h	130.0 €/h	5.8 m^3/h
Felling and processing with harvester – *Sječa i izradba drva harvesterom*	15.6 l/h	135.0 €/h	18.0 m^3/h
Extracting with forwarder (logs) – *Izvoženje forvarderom (oblo drvo)*	11.1 l/h	90.0 €/h	15.5 m^3/h
Extracting with forwarder (residues) – *Izvoženje forvarderom (šumski ostatak)*	11.1 l/h	90.0 €/h	4.0 m^3/h
Extracting with forwarder (tree) – *Izvoženje forvarderom (stabla)*	11.1 l/h	90.0 €/h	7.8 m^3/h
Extracting with skidder (stem) – *Privlačenje skiderom (debla)*	7.3 l/h	60.0 €/h	9.0 m^3/h
Extracting with skidder (tree) – *Privlačenje skiderom (stabla)*	7.3 l/h	60.0 €/h	10.0 m^3/h
Extracting with tower yarder (stem) – *Iznošenje stupnom kamionskom žičarom (debla)*	16.0 l/h	130.0 €/h	9.3 m^3/h
Extracting with tower yarder (tree) – *Iznošenje stupnom kamionskom žičarom (stabla)*	16.0 l/h	130.0 €/h	8.5 m^3/h
Extracting with shuttle (chips) – *Privlačenje šatlom (iver)*	10.0 l/h	88.0 €/h	17.1 m^3/h
Processing with processor – *Izradba procesorom*	8.0 l/h	110.0 €/h	10.0 m^3/h
Bundling – *Izradba svežnjeva*	11.5 l/h	120.0 €/h	4.9 m^3/h
Chipping with tractor & chipper (logs) – *Iveranje obloga drva – traktorom pokretani iverač*	34.8 l/h	140.0 €/h	67.0 m^3 loose/h
Chipping with tractor & chipper (residues) – *Iveranje šumskoga ostatka – traktorom pokretani iverač*	34.8 l/h	140.0 €/h	26.0 m^3 loose/h
Chipping with tractor & chipper (bundles) – *Iveranje svežnjeva – traktorom pokretani iverač*	34.8 l/h	140.0 €/h	54.0 m^3 loose/h
Chipping with tractor & chipper (trees) – *Iveranje stabala – traktorom pokretani iverač*	34.8 l/h	140.0 €/h	29.0 m^3 loose/h
Chipping with chipper on truck (logs) – *Iveranje obloga drva – iverač na kamionu*	40.5 l/h	220.0 €/h	134.0 m^3 loose/h
Chipping with chipper on truck (residues) – *Iveranje šumskoga ostatka – iverač na kamionu*	40.5 l/h	220.0 €/h	52.0 m^3 loose/h
Chipping with chipper on truck (bundles) – *Iveranje svežnjeva – iverač na kamionu*	40.5 l/h	220.0 €/h	108.0 m^3 loose/h
Chipping with chipper on truck (trees) – *Iveranje stabala – iverač na kamionu*	40.5 l/h	220.0 €/h	85.0 m^3 loose/h
Chipping with mobile chipper in stand (trees) – *Iveranje stabala pokretnim iveračem u sastojini*	28.0 l/h	155.0 €/h	17.0 m^3 loose/h
Transportation (logs) – *Prijevoz obloga drva*	40 l/100 km	80.0 €/h	
Transportation (residues) – *Prijevoz šumskoga ostatka*	25 l/100 km	65.0 €/h	
Transportation (bundles) – *Prijevoz svežnjeva*	40 l/100 km	82.0 €/h	
Transportation (trees) – *Prijevoz stabala*	25 l/100 km	65.0 €/h	
Transportation (chips) – *Prijevoz ivera*	50 l/100 km	67.0 €/h	

Sažetak

Razvoj višekriterijskoga alata za pomoć pri odlučivanju kod upravljanja dobavom energijskoga drva

Uporaba drva za ogrjev i proizvodnju energije pokazuje rast u posljednja dva desetljeća uz daljnji porast potražnje. Pridobivanjem se energijskoga drva može ostvariti dodatan izvor prihoda za šumovlasnike, koje općenito pozitivno djeluje na ekonomičnost šumskih operacija, ali i utječe na okolišne i socijalne čimbenike, poput ravnoteže u šumskom okolišu, uvjete rada, razinu zaposlenosti, što također treba vrednovanjem obuhvatiti. Pojedini se izvođači radova suočavaju s brojnim mogućnostima izbora sustava pridobivanja drva za energiju, uz često ograničeno znanje o njihovim značajkama. Također je važno shvatiti da pojedini izvođači radova često imaju različite predrasude u odnosu na ravnotežu između ekonomskih, okolišnih te socijalnih utjecaja pojedinih sustava pridobivanja drva za energiju.

U Microsoft Excelu, uz primjenu Visual Basic for Applications, razvijen je računalni program za potporu pri odlučivanju kao pomoć izvođačima radova u prepoznavanju najpogodnijega lanca dobave energijskoga drva s obzirom na njihove potrebe. Aplikacija uzima u obzir brojne kriterije, kao što su energetska učinkovitost, ravnoteža hraniva, stabilnost i vitalnost sastojine i tla nakon izvođenja radova, kontribucijska marža, jamstvo dobave, razina zaposlenosti te sigurnost pri radu. Korisnicima je omogućen unos stanišnih, sastojinskih te okolišnih podataka i tehnoloških parametara, kao i promjena postavki njihovih osobnih prioriteta za ravnotežu između pojedinih kriterija. Cjelokupna korisnost različitih mogućih postupaka izračunava se pomoću zbirnoga modela korisnosti, koja se grafički i tablično prikazuje na zaslonu računala.

Aplikacija je oblikovana radi prijenosa znanja stečenih tijekom istraživanja te predstavlja praktičan i razumljiv alat. Dodatno u predstavljanju alata za pomoć pri odlučivanju ovaj rad istražuje utjecaj ponderiranja kriterija, terenskih prilika, udaljenosti prijevoza te sadržaja vlage na odabir najpogodnijega lanca dobave energijskoga drva.

Ključne riječi: potpora odlučivanju, model korisnosti, upravljanje dobavom, energijsko drvo, pridobivanje biomase, planiranje gospodarenja šumom, višenamjensko šumarstvo

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Received (*Primljeno*): May 31, 2012
Accepted (*Prihvaćeno*): July 3, 2012