University for Natural Resources and Life Sciences, Vienna
Department of Forest and Soil Sciences

Multi-criteria efficiency gaps analysis of forest road networks and harvesting systems in the European mountains

Dissertation

in fulfilment of the requirements for the degree of
Doctor rerum naturalium technicarum (Dr.nat.techn.)

submitted by:
Dipl.-Ing. MScMF Dr. Adrian Enache

Supervisors:

Univ. Prof. Dipl.-Ing. Dr.nat.techn. Karl Stampfer
Assoc.Prof. Dr.nat.techn. Rien Visser
Univ.Prof.Dr.Ing. Valentina Doina Ciobanu

Vienna, 21st January 2016

TABLE OF CONTENTS

Abstract

Increasing the efficiency of forestry operations in European mountain regions is a complex task due to the multiple forest functions and the large number of factors that influence the decision-making process, such as terrain topography, accessibility, ownership structure, stakeholders' participation, silvicultural system, available machinery, technical limitations, forest workers' skills, environmental compatibility, social acceptance and economic viability. The aim of this thesis was to assess the efficiency gaps of forest road networks and harvesting systems in European mountains. The focus was on: *(i)* understanding the current practices in logging operations through multi-criteria scenario based analysis, *(ii)* developing an integrated support tool for decision-making, *(iii)* understanding stakeholders' interests related to forest operations, and *(iv)* assessing the environmental footprint of forest roads during their life cycle.

The analyses were conducted from 2012 to 2014 based on a number of more than 700 observed forest operations located in representative European mountain ranges. Planning, building and maintenance of forest roads, as well as execution of logging operations (thinnings and regeneration fellings) were observed and analyzed. GIS mapping and analysis, multiple criteria decision-making, empirical and statistical analysis of the observed parameters were conducted.

The following results are the major findings within this thesis:

(I) The mean road density in European mountain forests is 18.5 m ha^{-1} and the extraction distance is about 500 m. Skidding is the most commonly used extraction method, including in steep terrain. In timber felling and processing, the mean productivity is 9.0 m^3 ha^{-1} and the costs are 11.1 € m^{-3}. In timber extraction, the mean productivity is 10.2 m^3 ha^{-1} and the costs are 11.7 € m^{-3}. Fully mechanized harvesting systems reported the highest efficiency, the lowest number of accidents and the lowest stand damage.

(II) Through a scenario based analysis, the integrated decision support tool showed that reducing the extraction distance from 864 m to about 260 m would increase the productivity in timber extraction with about 56% for tractors and 58% for skidders, while to costs would decrease by 58% and 31% respectively. In addition, enhancing forest infrastructure could decrease the CO_{2eq} emissions from timber extraction and transport by 17% in the project area.

(III) The stakeholders' survey showed that the accessibility, the conservation of ecological valuable areas and the costs are the most relevant criteria of evaluating roads in mountain forests. Another finding was that the stakeholders have yet too little concern on risks and social factors related to forest engineering works. The study also reported a homogenous clustering of preferences by expertise groups; the forestry trained stakeholders assigned higher importance to indicators related to the implementation of forest management plans, while the groups with non-forestry backgrounds (i.e. NGOs, environmental agencies, tourists) assigned higher preferences to environmental and social indicators.

(IV) The hybrid LCA of forest roads showed that terrain topography has a strong influence on the environmental burden of forest roads. The amount of energy required for road construction was 312.6 MJ m^{-1} in steep and stony terrain, and 223.1 MJ m^{-1} on gentle slopes with no rock outcrops. Embankment and pavement works accounted for about 90% of the energy input in both cases. The CO_{2eq} emissions were 22.9 kg m^{-1} in the former case and 16.6 kg m^{-1} in the latter case. Another finding was that road maintenance works are very energy intensive; they are comparable to the energy demand of road construction. Road maintenance demands about 17.9 MJ m^{-1} per event. That is 267.8 MJ m^{-1} over the road life cycle and CO_{2eq} emissions of 20.1 kg m^{-1}.

1. Introduction

1.1 Problem statement

Forests cover 42% of European land area (Eurostat 2015) and 41% of the European mountain areas (Price et al. 2011). As such, they must ensure lasting provision of ecosystem services and they must adapt and mitigate the effects of climate changes for contributing to a better carbon balance and a greener economy with optimized socio-economic benefits. The Oslo Ministerial Decision (Forest Europe 2011) and the EU Forest Strategy (European Commission 2013) define the framework for sustainable forest management (SFM) in Europe and advocate a holistic approach of the management in the forest-value chain. The Europe 2020 targets on climate change and use of energy (European Commission 2010) and the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC 2015) call for reduction of greenhouse gas emissions and improvement of energy efficiency in all sectors, including the forest-based industries.

Mountain forests provide multiple ecosystem services (ES), *inter alia*, timber production, carbon storage, biomass for bioenergy, nature conservation, protection against natural hazards, wildlife management, provision of drinking water and recreational functions (Diaci et al. 2011; O'Hara and Ramage 2013; Stupak et al. 2007). Given their multidimensionality, they often are subject to simultaneous conflicting objectives and therefore, issues like sustainable timber production, maintaining biodiversity, ensuring multiple-use of forests, climate change mitigation, public participation and implementing adaptive management are some of the most important challenges which need to be currently addressed in forest management planning (Vacik and Lexer 2014). With the growing interest for close-to-nature forest management and multiple-use forestry (Brang et al. 2014), timber production remains an important ES of mountain forests.

Well-developed forest road networks are fundamental for the implementation of SFM. They facilitate the access to stands and the execution of silvicultural and engineering works such as planting, tending, thinning, regeneration felling, timber extraction and timber transport (Abrudan et al. 2009). Forest roads also serve for accessing remote areas in case of accidents (i.e. forest workers, tourists), natural hazards (i.e. forest fires, wind-throws), for tourism and recreational purpose, particularly in mountain areas (Popovici et al. 2003; Pellegrini et al. 2013; Ciesa et al. 2014). The quality and the layout of forest road networks have a significant influence on the economic efficiency, environmental footprint and social impact of the wood supply chain management (Stampfer and Kanzian 2006; Kühmaier and Stampfer 2010; Holzleitner et al. 2011a).

There are a number of factors influencing the efficiency of forestry operations in European mountains, such as: terrain topography, silvicultural system, tree size, method of harvesting, degree of mechanization, type of machinery, technical limitation, extraction distance and forest workers' know-how and skills (Berg et al. 2012, 2014; Borz et al. 2013; Eriksson and Lindroos 2014; Ghaffariyan et al. 2010; Holzleitner et al. 2011b; Laitila et al. 2007; Nurminen et al. 2006; Spinelli et al. 2004; Talbot et al. 2003; Vusić et al. 2013). When not adequately addressed in the planning process, these factors lead to efficiency gaps such as low productivity, high costs, increased environmental footprint and negative social impact. Challenging problems as such, especially in the frame of the increasing environmental awareness and social responsibility, forest operations have to be carefully planned and executed. Thus, complex forest engineering decision problems need to be solved, such as planning and optimizing the location of forest road networks, maintenance of forest road networks, selection of harvesting systems, and addressing relevant stakeholders' interests and considering the sustainability principles.

In this frame of multidimensional forest engineering issues, multi-criteria analysis and decision support systems (DSS) can be a useful approach to decision making. Problem structuring is a prerequisite for any decision support process and the approaches used in this respect vary in their scope and complexity (Mingers and Rosenhead 2004). Finding the most suitable solution from a set of technically feasible alternatives in forest management can be facilitated using GIS and multiple criteria decision-making (MCDM). There are different MCDM methods suitable for dealing with forest management decisions (Ananda and Herath 2009; Diaz-Balteiro and Romero 2008; Kangas and Kangas 2005; Kangas et al. 2008). The multiple attribute utility theory (MAUT) and the analytic hierarchy process (AHP) are the most commonly used ones in strategic and tactical planning of forest operations; they can deal with risk and uncertainties and they allow performing sensitivity analysis (Coulter et al. 2006; Kühmaier and Stampfer 2010, 2012; Kühmaier et al. 2014; Pellegrini et al. 2013; Talbot et al. 2014). Optimization techniques, programming and modelling are often used (Flisberg et al. 2014; Kangas et al. 2014; Kanzian et al. 2013; Marques et al. 2014). The decision models do not provide ready-made decisions, but they support and facilitate the decision making process through utility, sensitivity and qualitative analyses of the decision alternatives (Vacik and Lexer 2014).

Therefore, assessing the efficiency gaps of forest road networks and timber harvesting systems in the European mountains is a necessary process for improving the overall performance of forest operations in compliance with the sustainability principles.

1.2 Goal and objectives

The aim of this thesis is to assess the economic, ecological and social gaps of forest road networks and harvesting systems in European mountains from a multidimensional perspective, using analytical methods, DSS and MCDM. The thesis also analyzes the environmental performance of forest roads during their lifecycle. The focus is on assessing the planning, construction and maintenance of forest roads, and the degree of mechanization and the efficiency of harvesting systems. Productivity, costs, embodied energy and emissions of machinery used in forest road engineering, as well productivity, costs, environmental and social impact of harvesting systems are analyzed in three publications and social responsibility aspects in planning forest road networks are approached in one publication.

In detail, the main objectives of this thesis are:

1. To improve the understanding of current practices in logging operations in European mountain forests and to identify the existing efficiency gaps based on a multidimensional approach related to, *inter alia*, forest infrastructure, mechanization degree, timber harvesting and extraction methods (Publication I);
2. To develop an integrated decision support tool for evaluating forest road options in mountain areas using GIS and multiple criteria analysis (Publication II);
3. To analyze and better understand stakeholders' interests, and to strengthen the social responsibility related to forest engineering issues (Publication III);
4. To assess the environmental footprint of forest roads during their lifecycle (i.e. road construction and maintenance works), based on a hybrid life cycle assessment (LCA) approach (Publication IV).

2. Material and methods

2.1 General thesis layout

The thesis focuses on four interlinked topics regarding forest infrastructure and timber harvesting systems (Figure 1).

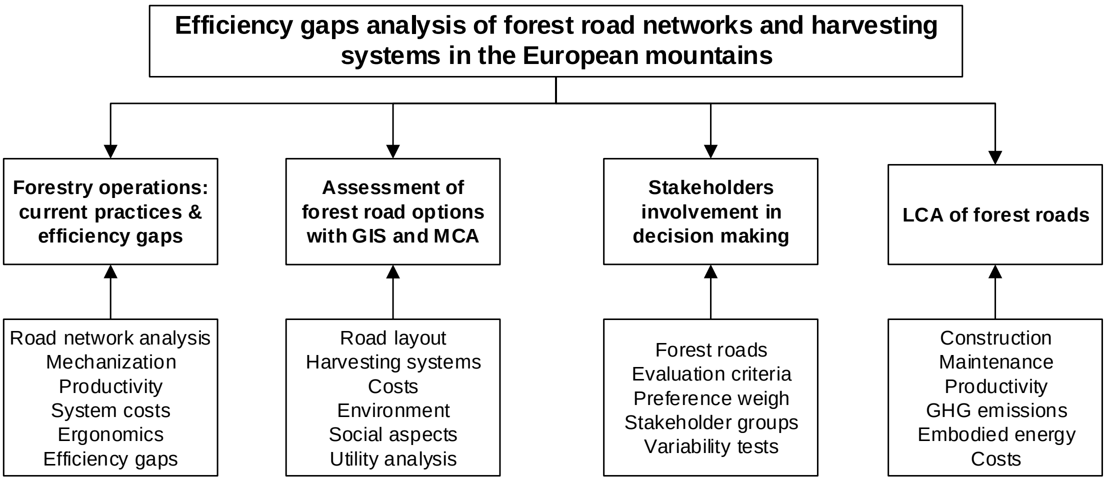


Figure 1 Thesis structure with covered topics and analysed issues

For assessing the efficiency gaps of forest road networks and harvesting systems, a number of 632 forest operations performed between 2012 and 2013 were analyzed. They were located in seven case study areas (CSA) in representative European mountain ranges which covered the most important forest types: Rhodope Mountains, Carpathian Mountains, Scandinavian Mountains, Dinaric Mountains, Eastern Alps, Western Alps and Iberian Mountains. For the assessment of forest road options, multiple attribute utility theory (MAUT) and GIS analysis were used to develop an integrated decision support tool that was tested and validated in community forests from Southern Carpathians. The issue of social responsibility and the assessment of stakeholders' perception regarding evaluation criteria of forest roads were addressed based on a survey conducted in 2012 in Romania. The environmental performance of forest roads for a life cycle of 30 years was assessed in two case study areas located in Eastern Carpathians, using a hybrid input-output LCA.

2.2 Data collection and processing

For assessing the current practices in logging operations in European mountains, descriptive statistics and frequency analysis were performed at stand, landscape and case study area level using PASW Statistics18®. The following types of indicators were analyzed: road density, road construction and maintenance costs, degree of mechanization, harvesting method, extraction method, harvested species, harvesting productivity and cost, extraction distance, extraction productivity and cost.

For the evaluation of forest road options, a multi-criteria decision model was developed using ESRI® Arc GIS Desktop 10 and Microsoft Office Excel® for data processing. Indicators such as road network density, mean extraction distance, accessibility, productivity, system costs, environmental compatibility and social impact were analyzed. GIS datasets, data from forest management plans and intermediate results from previous qualitative and quantitative analysis were used as input in the overall utility analysis of the decision alternatives.

The involvement of stakeholders in decision-making in forest engineering focused on rating selected evaluation criteria of forest roads. A survey was conducted through a structured web-based questionnaire and statistical analyses of the significance of responses of twelve stakeholder groups were performed in PASW Statistics18®. Empiric analysis and graphic interpretation of the results in Microsoft Office Excel® were also performed.

The LCA of forest roads was performed in two case study areas (CSA) from Eastern Carpathians. For each CSA, the data was collected from the records of a private forest enterprise for the following machinery: chainsaw, excavator, stone crusher, grader, front loader, backhoe loader, compactor, dump truck, trailer and timber lorry. Direct energy requirements and greenhouse gas emissions were derived from the machinery fuel consumption to carry out specific tasks (Whittaker et al. 2011). Technology matrices (Heinimann 2012) were developed in Microsoft Office Excel®, cost appraisals and assessment of systems' performance were conducted for each phase of the road construction and maintenance works.

2.3 Approaches for decision support

The thesis focused on using multi-criteria analysis for supporting decisions in forest engineering. In forest management, DSS can be designed for solving specific problems or for addressing general issues in a holistic and flexible manner at various scales, such as stand, landscape, watershed or regional level (Vacik and Lexer 2014). In forest engineering, DSS are useful for addressing decision problems both at broader and smaller scale. At broader scale (e.g. watershed, landscape, forest district), DSS can be used for planning and building new forest roads networks or for setting priorities in forest roads maintenance either for scheduling timber harvesting operations. At smaller scale (e.g. forest stand), DSS focus on selection of suitable harvesting systems. However, it is not always a clear edge between these scales, since selection of harvesting systems and forest road network planning are interlinked and hence they require an integrated approach (Flisberg et al. 2014).

At broader scales and for long-term perspectives, when decision makers need an overview of the suitability of harvesting systems or related to possible options for developing the road network at forest enterprise level, generic models can be developed for decision support as follows:

1. Elaborate a list of decision alternatives (e.g. harvesting systems, road options)
2. Define independent attributes that influence the selection of alternatives
3. Weigh the importance of attributes through pair wise comparisons
4. Define classes of performance for each independent attribute
5. Score or rate the performance of decision alternatives by each attribute
6. Calculate the total score of decision alternatives by compounding the individual attribute scoring with the weight of each attribute
7. Rank the decision alternatives according to the total score

This generic approach has no spatial component and may be used in strategic planning for setting general directives and for establishing investment priorities with long-term perspective at top-level management (Eriksson et al. 2014), such as the need of first opening-up of forests with primary forest roads. AHP can be used to weight the importance of attributes (Saaty 2008). The scoring of decision alternatives by attributes can be done with the simple multiple attribute ranking technique (SMART; von Winterfeldt and Edwards 1986). The score of decision alternatives by attributes have to be normalized to utility values between zero and one (Kangas et al. 2008). The best alternative is assumed to have value one and the worst the value zero. This can be done either with the maximum score based approach or with the score range procedure (Kangas et al. 2008). The utility score of each decision alternative by attribute is then calculated by multiplying the normalized utility value of the alternative with the weight of the attribute. The total utility score of a decision alternative results as the sum of the utility scores of that alternative for each attribute. This generic method can be used for benchmarking scenarios and for identifying efficiency gaps.

In tactical planning of forest operations, middle management has to set priorities of intervention with medium term perspective at smaller scale. Decisions regarding selection of harvesting systems for specific terrain-stand conditions and about construction of new forest roads or for maintaining the existing road network have to be made. These situations require more complex DSS with a spatial component. GIS provides good opportunities for improving the analyses through input, storage and use of spatial information on one hand, and incorporation of MCDM mechanisms for modelling trade-offs between scenarios with multiple conflicting objectives on the other hand (Vacik and Lexer 2014).

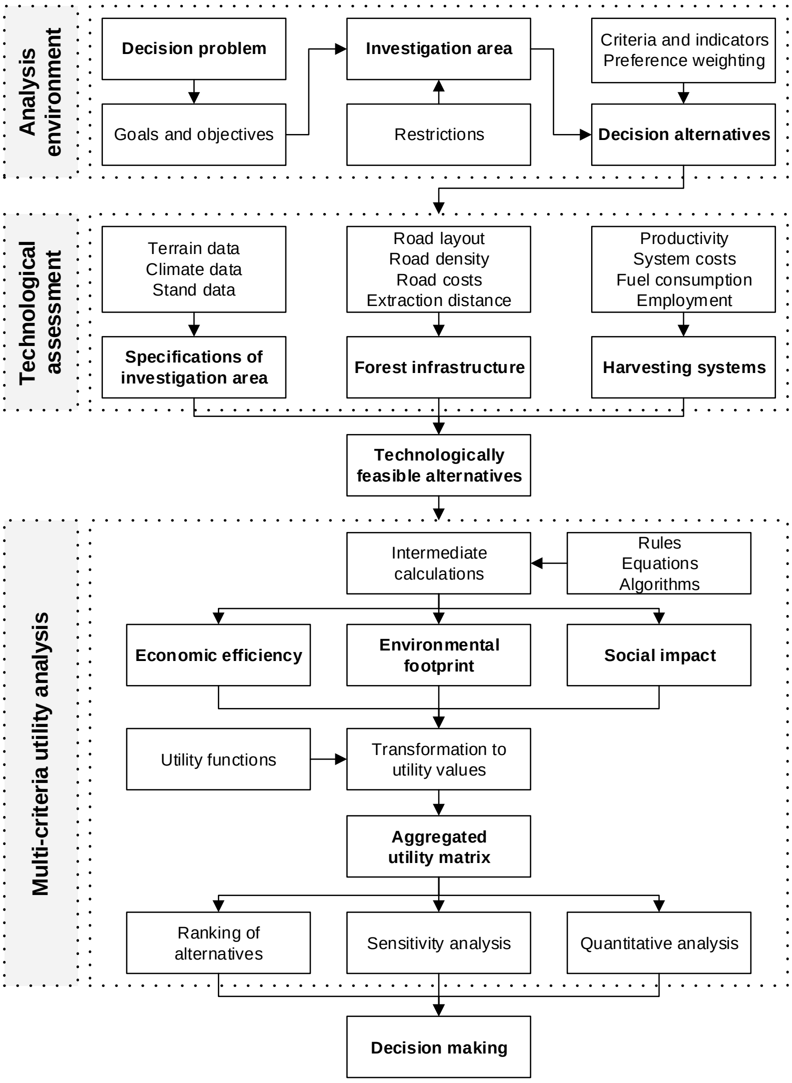


Figure 2 Example of a multi-criteria evaluation process flow of forest operations

Defining the analysis framework and designing the decision model are prerequisite in developing a spatial DSS. The first steps are to define the decision problem, the system to be modelled and its borders. Then, the decision model that depicts the process flow of data and information throughout the decision process is designed (Kühmaier and Stampfer 2012). Figure 2 shows the process flow and interlinks between components of a spatial decision model developed for assessing forest road and harvesting system scenarios. The model is structured in three main phases, out of which the description of the analysis framework and the technological assessment require the use of GIS.

2.4 GIS analysis

GIS tools were used for spatial analysis, process automation, and for defining and integrating spatial layers with restrictions and preferences required in the decision process. Such layers include, *inter alia,* slope classes, terrain fragmentation, accessibility, stream network, tree species, DBH classes, forest management systems, biodiversity hot spots, protected areas and location of facilities (e.g. landing areas).

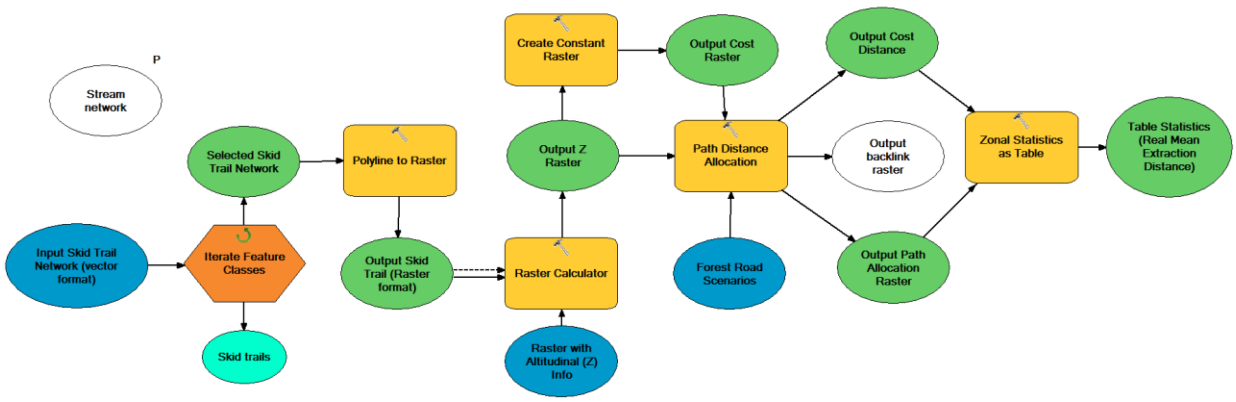


Figure 3 GIS model for computing the mean extraction distance in a forest area

The *Model Builder*™ extension in ESRI® ArcGIS was used to combine workflows in interactively linked sequences using DEMs, GIS datasets and results of previous calculations in order to make calculations faster and easier (Allen 2011). Iterating features were used to iterate through input datasets and scenarios (i.e. decision alternatives). Figure 3 shows an example of a GIS model elaborated for calculating the mean extraction distance in a defined project area where the skid trail network was previously mapped in GIS. The model determines the least accumulative path distance for each cell of the skid trail raster to the nearest road, considering horizontal and vertical constraints.

3. Synthesis of results

Generally, the efficiency gaps analysis (EGA) of forest road networks and timber harvesting systems in mountain forests refer to quantitative and qualitative assessment of representative indicators, including productivity, costs, utilization rates and environmental performance of machinery. Considerable amount of data regarding density of road networks, road costs, timber transport costs, timber harvesting and extraction methods, productivity and costs, emissions and energy requirements were covered in this thesis and are now available as benchmarks for future research dealing with these topics. In addition, EGA addressed the planning of forest operations; a multi-criteria decision support tool for locating forest roads, GIS methods for analysing road networks and a LCA model for assessing environmental performance of forest roads were also developed and comprehensively documented. These outputs are useful *per se* in practice and in further studies referring to management of forest road networks. They also serve as reference for other studies or as an input for extended support tools dealing with decision-making problems in forest engineering.

3.1 Main results

Table 1 shows the main variables analyzed in the publications.

Table 1 Main variables analyzed in the publications

Variable	Unit	Publication
Road density	m ha^{-1}	I, II, IV
Road construction costs	€ m^{-1}	I, II, IV
Road maintenance costs	€ m^{-1}	I, II, IV
Extraction distance	m	I, II, IV
Fuel consumption	litters PSH_{15}^{-1}	IV
Machinery costs	€ PSH_0^{-1}	IV
Energy efficiency forest roads	MJ m^{-1}	IV
CO_{2eq} emissions forest roads	kg m^{-3}	IV
CO_{2eq} emissions harvesting systems	kg m^{-3}	I, II
Harvesting productivity	m^3 PSH_{15}^{-1}	I, II
Harvesting costs	€ m^{-3}	I, II
Timber extraction productivity	m^3 PSH_{15}^{-1}	I, II
Timber extraction costs	€ m^{-3}	I, II
Timber transport costs	€ m^{-3}	I, II

The findings of this thesis extended the existing knowledge database regarding performance indicators of harvesting systems and machinery used in road construction and maintenance in European mountain forests. They are valuable for future research, in particular those referring to utilization rates, productivity, costs and environmental performance of machinery used in road construction and maintenance (Table 2 and Table 3), which previously were not extensively covered in the literature.

Table 2 Productivity of machinery used in road construction and maintenance

Machine type	Road construction ($m\ h^{-1}$)		Road maintenance ($m\ h^{-1}$)
	Moderate terrain (MT)*	Difficult terrain (DT)*	
Excavator	4.6	3.0	-
Stone crusher	15.2	13.4	416.7
Grader	21.1	39.3	178.6
Front loader	8.5	6.3	-
Backhoe loader	-	-	23.3
Compactor	29.9	16.1	357.1
Dump truck	4.8	4.1	62.5
Trailer	71.1	56.2	500.0

***Note:** MT: 1% stony material and slopes < 40%; DT: 60% stony material and 50% of the road length with slopes > 40%

Table 3 Energy efficiency in road construction and maintenance

Type of operation	Road construction ($MJ\ m^{-1}$)		Road maintenance ($MJ\ m^{-1}$)
	Moderate terrain (MT)*	Difficult terrain (DT)*	
Preparatory works	8.9	19.4	-
Embankment works	86.4	181.4	-
Drainage system	12.0	11.2	164.7
Pavement works	115.8	100.6	103.1
TOTAL	223.1	312.6	267.8

* MT - 1% stony material and slopes < 40%; DT - 60% stony material and 50% of the road length with slopes > 40%

In addition, a multi-criteria decision support tool for assessing forest road alternatives was developed and an analysis of stakeholders' preferences on evaluation criteria of forest roads was conducted, with the aim to better document and facilitate the decision-making process in forest engineering.

3.2 Limitations

Given the significant size and fragmentation of the areas covered in Publication I, the analysis of the forestry operations in European mountains employed real observed data collected from forest enterprises and not on time studies. Thus, the study lacked a more analytical experimental design approach. This was balanced by quantitative, qualitative and statistical analyses of a considerable number of the observed parameters.

The quality of the GIS analysis depends on the accuracy of the digital elevation models (DEM). Although using high resolution DEMs (usually 5X5 m or 1X1 m) is recommended, such accurate data was not always available in all studied areas, and DEMs with resolutions up to 20X20 m were used instead (Publications I and II). The low resolution might affect the accuracy of GIS analysis when certain analyzed parameters require a high level of detail (e.g. terrain fragmentation and off-road trafficability analysis). The DEM resolution has a lower impact on spatial analysis when broader scale parameters are analyzed to describe general trends.

Involving the relevant stakeholders in the decision-making process related to forest engineering problems is very important, but also rather challenging. It was noted (Publication III) that the online surveys are not the best method for involving stakeholders in decision-making due to possible low response rate, reduced level of flexibility in describing and discussing the analyzed issues and parameters, and lack of face-to-face interaction between stakeholders. However, the methodology presented in Publication III can be applied in practice in the form of workshops, decision conferencing or round table discussions, fostering active and direct participation of the relevant stakeholders.

The life cycle analysis of forest roads (Publication IV) did not use a *"cradle to the grave"* approach. That is, the embodied energy in the manufacturing of the machinery used for road construction and maintenance was not included in the analysis. Instead, a hybrid LCA approach was applied to material, energy, and emission flows in each phase of the road construction and maintenance works (i.e. transport of machinery to the site, clearing the roadbed, construction of embankments, drainage system and pavement finishing).

3.3 Outlook

This thesis gives an insight on how to approach the current challenges regarding planning and execution of forestry operations in mountain forests. The research outputs do not cover all complex forest engineering issues, but they serve as best practice examples of how structured approaches of the decision problems can facilitate decision-making through multi-criteria analysis and GIS based tools that are better adapted to the needs of end-users in forest management.

DSS with integrative, flexible and transparent approaches, which have user-friendly interfaces and address specific target topics and audiences, are required in the future (Vacik and Lexer 2014). Therefore, future research in forest engineering should focus on utilization of optimization techniques, methods and models for developing integrated forest operation plans and smart tools for improving the efficiency of allocation and utilization of resources. Ideally, these plans should jointly address specific interlinked issues such as the selection of suitable harvesting systems for specific conditions, timber harvesting scheduling and management of forest road networks (e.g. planning, building and maintenance) using GIS and MCDM. An example in this respect is the integrated model presented by Flisberg et al. (2014) for tactical planning of harvesting, transport and road management using a sequential approach. A strong focus should be given to developing smart and user-friendly tools in line with the developing trends of information technology (Vacik and Lexer 2014). For bridging the gaps between different hierarchical decision levels in forest management, these smart tools should have a multi-level approach, from strategic towards tactical and operational level. However, the level of detail required in planning at different spatial and time scales is significantly different, lower at larger scales (i.e. strategic planning) and higher at smaller scales (i.e. operational planning). This generates complex integration problems, but bottom-up and hierarchic optimization approaches could help integrating these different planning scales (Eriksson et al. 2014; Kangas et al. 2014). Availability of quality data is another critical issue, since it strongly influences the accuracy of the performed analysis. Process automation in data collection, analysis and management through SQL-routines (Holzleitner et al. 2013) and GIS modelling (Allen 2011) are valuable for handling data collection and analysis. For spatial analysis, LiDAR datasets have proved to be useful in forest engineering (Heinimann and Breschan 2012; White et al. 2010). Although such accurate datasets are not always available, the new developments in technology suggest that unmanned air vehicles could be a feasible solution for collecting and analyzing high-resolution spatial data for forest management purposes (Merino et al. 2012; Pierzchala et al. 2014). Not at least, more focus should be put on research about social responsibility in forestry sector, and in particular related to forest engineering, in order to strengthen the transparency in decision-making and to facilitate the elaboration and implementation of forest operation plans adapted to the stakeholders’ interests.

4. Acknowledgments

I would like to thank all those who contributed directly or indirectly to the elaboration of this entire work.

I express my highest gratitude to my family for supporting me during these years with their invaluable care, patience and confidence. My special thoughts go to my nephew David who gave me positive energy whenever I felt exhausted. I also thank all my friends for their advices and unconditioned support.

My sincere appreciations and gratitude go to my distinguished supervisors, to all my colleagues from the Institute of Forest Engineering (BOKU), to my co-authors, reviewers and peer-reviewers for their valuable input, comments and suggestions during the elaboration and revision process of the publications.

I would also like to thank all persons involved in providing input in various phases of their elaboration, and in particular to the representatives of *Ciucas Autonomous Forest Administration* and *Lignum Forest Enterprise* from Romania for their support in data collection and analysis. Finally yet importantly, I would like to acknowledge the following funding programs and institutions for their financial support:

- European Social Fund and Romanian Government – Sectoral Operational Programme Human Resource Development – SOP HRD ID76945,
- CEEPUS – Central European Exchange Program for University Studies,
- European Union Erasmus Life Long Learning Programme,
- European Community Seventh Framework Programme (FP7/2007-2013) – Grant No. 289437 – ARANGE Project.

5. References

Abrudan I.V., Marinescu V., Ionescu O., Ioras F., Horodnic S.A., Sestras R. (2009): Developments in the Romanian forestry and its linkages with other sectors. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 37(2):14-21.

Allen D.W (2011): Getting to know ArcGIS® Model Builder™. Esri Press, 320 p.

Ananda J., Herath G. (2009): A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecological Economics* 68(10):2535-2548.

Berg S., Fischbach J., Brüchert F., Poissonnet M., Pizzirani S., Varet A., Sauter U.H. (2012) Towards assessing the sustainability of European logging operations. *European Journal of Forest Research* 131(1):81-94.

Berg S., Schweier J., Brüchert F., Lindner M., Vlainger E. (2014) Economic, environmental and social impact of alternative forest management in Baden-Württemberg (Germany) and Västerbotten (Sweden). *Scandinavian Journal of Forest Research* 29(5):485-498.

Borz S.A., Dinulica F., Birda M. et al. (2013): Time consumption and productivity of skidding silver fir (Abies alba Mill.) round wood in reduced accessibility conditions: a case study in wind-throw salvage logging from Romanian Carpathians. *Annals of Forest Research* 56(2):363-375.

Brang P., Spathelf P., Larsen J.B. et al. (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* 0:1-12, doi:10.1093/forestry/cpu018

Ciesa M., Grigolato S., Cavalli R. (2014): Analysis on vehicle and walking speeds of search and rescue ground crews in mountain areas. *Journal of Outdoor Recreation and Tourism* 5-6:48-57.

Coulter E.D., Session J., Wing M.G. (2006): Scheduling forest road maintenance using the analytic hierarchy process and heuristics. *Silva Fennica* 40(1):143-160.

Diaci J., Kerr G., O'Hara K. (2011): Twenty-first century forestry: integrating ecologically based, uneven-aged silviculture with increased demands on forests. *Forestry* 84(5):463-465.

Diaz-Balteiro L., Romero C. (2008): Making forestry decisions with multiple criteria: A review and an assessment. *Forest Ecology and Management* 255(8-9):3222-3241.

Eriksson M., Lindroos O. (2014): Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *International Journal of Forest Engineering* 25(3):179-200.

Eriksson M., Wahlberg O., Nilsson M. (2014): Questioning the contemporary forest planning paradigm: making use of local knowledge. *Scandinavian Journal of Forest Research* 29(1):56-70.

European Commission (2010): Communication from the Commission: Europe 2020 – A strategy for smart, sustainable and inclusive growth COM (2010) 2020, 37p.

European Commission (2013): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new EU Forest Strategy: for forests and the forest-based sector – COM (2013) 659 final.

Eurostat (2015): Statistics explained. Forestry statistics [Internet]. [cited 2015 Mar 23] Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Forestry_statistics.

Flisberg P., Frisk M., Rönnqvist M. (2014): Integrated harvest and logistic planning including road upgrading. *Scandinavian Journal of Forest Research* 29(1): 195-209.

Forest Europe (2011): Oslo Ministerial Decision: European Forests 2020 [Internet]. [cited 2015 Jan 15]. Available from: http://www.foresteurope.org/docs/MC/MC_oslo_decision.pdf.

Ghaffariyan M.R., Stampfer K., Sessions J. (2010): Optimal road spacing of cable yarding using a tower yarder in southern Austria. *European Journal of Forest Research* 129(3):409-416.

Heinimann H.R. (2012): Life cycle assessment (LCA) in forestry – state and perspectives. *Croatian Journal of Forest Engineering* 33(2):357-372.

Heinimann H.R., Breschan J. (2012): Pre-harvest assessment based on LiDAR data. *Croatian Journal of Forest Engineering* 33(2):169-180

Holzleitner F., Kanzian C., Stampfer K. (2011a): Analyzing time and fuel consumption in road transport of round wood with an on-board fleet manager. *European Journal of Forest Research* 130 (2):293-301.

Holzleitner F., Stampfer K., Visser R. (2011b): Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croatian Journal of Forest Engineering* 32(2):501-508.

Holzleitner F., Kanzian C., Höller N. (2013): Monitoring the chipping and transportation of wood fuels with a fleet management system. *Silva Fennica* 47(1), 11p., dx.doi.org/10.14214/sf.899

Kangas A., Kangas J. (2005): Multiple criteria decision support in forest management - the approach, methods applied, and experiences gained. *Forest Ecology and Management* 207 (1-2):133-143.

Kangas A., Kangas J., Kurttila M. (2008): Decision support for forest management. Springer Science+Business Media B.V., 223 p.

Kangas A., Nurmi M., Rasinmäki J. (2014): From a strategic to a tactical forest management plan using a hierarchic optimization approach. *Scandinavian Journal of Forest Research* 29(1):154-165.

Kanzian C., Kühmaier M., Zazgornik J., Stampfer K. (2013): Design of forest energy supply networks using multi-objective optimization. *Biomass and bioenergy* 58:294-302.

Kühmaier M., Stampfer K. (2010): Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. *Croatian Journal of Forest Engineering* 31(2):75-88.

Kühmaier M., Stampfer K. (2012): Development of a multi-criteria decision support tool for energy wood supply management. *Croatian Journal for Forest Engineering* 33(2):181-198.

Kühmaier M., Kanzian C., Stampfer K. (2014): Identification of potential energy wood terminal locations using a spatial multi-criteria decision analysis. *Biomass and Bioenergy* 66:337-347.

Laitila J., Asikainen A., Nuutinen Y. (2007): Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. *International Journal of Forest Engineering* 18(2):29-39.

Marques A.F., de Sousa G.P., Rönnqvist M., Jafe R. (2014): Combining optimization simulation tools for short-term planning of forest operations. *Scandinavian Journal of Forest Research* 29(sup1):166-177

Merino L., Caballero F., Ramiro Martinez-de-Dios J., Maza I., Ollero A. (2012): An unmmaned aircraft system for automatic forest fire monitoring and measurement. *Journal of Intelligent and Robotic Systems* 65(1):533-548.

Mingers J., Rosenhead J. (2004): Problem structuring methods in action. *European Journal of Operational Research* 152(3):530-554

Nurminen T., Korpunen H., Uusitalo J. (2006): Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica* 40(2):335-363.

O’Hara K.L., Ramage B.S. (2013): Silviculture in an uncertain world: utilizing multi-aged management to integrate disturbance. *Forestry* 86:401–410.

Pellegrini M., Grigolato M., Cavalli R. (2013): Spatial multi-criteria decision process to define maintenance priorities of forest road network: an application in the Italian Alpine Region. *Croatian Journal of Forest Engineering* 34(1):31-42.

Pierzchala M., Talbot B., Astrup R. (2014): Estimating soil displacement from timber extraction trails in steep terrain: application of an unmanned aircraft for 3D modelling. *Forests* 5(6):1212-1223.

Popovici V., Bereziuc R., Clinciu I. (2003): Extension of road network for improving the access to forests and forest fund. [In Romanian]. *Bucovina Forestiera* XI(2):36-40.

Price M.F., Gratzer G., Duguma L.A., Kohler T., Maselli D., Romeo R. ed. (2011): Mountain Forests in a Changing World - Realizing Values, addressing challenges. Rome (Italy): FAO/MPS 2 and SDC, 86 p.

Saaty T. (2008): Decision making with the analytic hierarchy process. *International Journal of Services Sciences* 1(1):83 - 98

Spinelli R., Owende P.M.O., Ward S.M., Tornero M. (2004): Comparison of short-wood forwarding systems used in Iberia. *Silva Fennica* 38(1):85-94.

Stupak I., Asikainen A., Jonsell M., Karltun E., Lunnan A. et al. (2007): Sustainable utilisation of forest biomass for energy – possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. *Biomass and Bioenergy* 31:666-684.

Stampfer K., Kanzian C. (2006): Current state and development possibilities of wood chip supply chains in Austria. *Croatian Journal of Forest Engineering* 27(2):135-145.

Talbot B., Nordfjell T., Suadicani K. (2003): Assessing the utility of two integrated harvester-forwarder machine concepts through stand-level simulation. *International Journal of Forest Engineering* 14(2):31-43.

Talbot B., Tarp P., Nitteberg M. (2014): Selecting an appropriate excavator-based yarder concept for Norwegian conditions through the analytic hierarchy process. *International Journal of Forest Engineering* 25(2):113-123

United Nations Framework Convention on Climate Change – UNFCCC (2015): The Paris Agreement under the United Nations Framework Convention on Climate Change, 12th December 2015

Vacik H., Lexer M.J. (2014): Past, current and future drivers for the development of decision support systems in forest management. *Scandinavian Journal of Forest Research* 29(1): 2-19.

Vusić D., Susnjar M., Marchi E., Spina R., Zecic Z., Picchio R. (2013) Skidding operations in thinning and shelterwood cut of mixed stands – work productivity, energy inputs and emission. *Ecological Engineering* 61:216-223.

White A.R., Dietterick B.C., Mastin T., Strohman R. (2010): Forest roads mapped using LiDAR in steep forested terrain. *Remote Sensing* 2010(2):1120-1141.

Whittaker C., Mortimer N., Murphy R., Matthews R. (2011): Energy and greenhouse gas balance of the use of forest residues for bioenergy production in UK. *Biomass and Bioenergy* 35(11):4581-4594

von Winterfeldt D., Edwards W. (1986): Decision analysis and behavioural research. Cambridge University Press, 624 p.

6. Appendix – Publications

Publication I

Enache A., Kühmaier M., Visser R., Stampfer K. (2016): Forestry Operations in the European Mountains: A study of current practices and efficiency gaps. *Scandinavian Journal of Forest Research* DOI:10.1080/02827581.2015.1130849

Publication II

Enache A., Kühmaier M., Stampfer K., Ciobanu D.V. (2013): An integrative decision support tool for assessing forest road options in a mountainous region in Romania. *Croatian Journal of Forest Engineering* 34(1):43-60.

Publication III

Enache A., Ciobanu D.V., Stampfer K. (2015): Stakeholders' perceptions regarding evaluation criteria of forest road options in Romania. *Environmental Engineering and Management Journal* 14(6):1409-1421.

Publication IV

Enache A., Stampfer K. (2015): Machine utilization rates, energy requirements and greenhouse gas emissions of forest road construction and maintenance in Romanian mountain forests. *Journal of Green Engineering* 4(4):325-350.

Publication I

Accepted 8th December 2015 – published online

SCANDINAVIAN JOURNAL OF FOREST RESEARCH, 2016
http://dx.doi.org/10.1080/02827581.2015.1130849

Taylor & Francis
Taylor & Francis Group

Adrian Enache[a], Martin Kühmaier[a], Rien Visser[b] and Karl Stampfer[a]

[a]Institute of Forest Engineering, University of Natural Resources and Life Sciences, Vienna, Austria; [b]School of Forestry, University of Canterbury, Christchurch, New Zealand

ABSTRACT
Timber production is an important ecosystem service of European mountain forests. This paper aimed to assess the current practices in logging operations and to identify the efficiency gaps in timber production. The study was located in 7 case study areas from representative European mountain ranges, where 632 logging operations were analysed. The focus was on road infrastructure, transport systems, harvesting methods and extraction technologies. Often inappropriate technology was used in steep terrain; there was no correlation between the average slope and the selection of harvesting systems (HS). Skidding was the most common extraction method (75%), while cable yarding and forwarding had shares of 15% and 8%. The mean road density was 18.5 m ha^{-1}. The mean extraction distance was 501 m. The mean harvesting and extraction productivity were 9.0 and 10.2 $m^3 h^{-1}$; the mean costs were 11.1 and 11.7 € m^{-3}, respectively. Non-mechanized and obsolete HS reported the lowest efficiency and the highest environmental footprint, while fully mechanized systems reported the highest efficiency, the lowest number of accidents and the lowest stand damage. Cable yarders are the appropriate extraction technology in steep terrain, but they require a well-developed road network. Higher mechanization degree, improved quality of the road networks, knowledge transfer to practice and training of forest workers are some of the necessary measures to overcome the efficiency gaps in timber production in European mountain forests.

Received 1 April 2015
Accepted 8 December 2015

Forest roads; harvesting method; mechanization; productivity; steep terrain; timber extraction

Forests cover about 42% of the European Union (EU) land area (Eurostat 2015) and about 41% of the total EU mountain areas (Price et al. 2011). The minimum elevation of mountain areas varies by country between 250 and 1000 m and, usually, there is a decrease in the altitude threshold from southern to northern European countries (Nordregio 2004). Mountain forests provide goods and services essential to the livelihood of both highland and lowland communities, that is a wide variety of ecosystem services (ES), from protection against rockfall, avalanches and torrential flows up to high quality drinking water, wildlife habitats, landscape scenic beauty, timber production and carbon sequestration (Forest Europe et al. 2011; Price et al. 2011). Therefore, the management of mountain forests should be approached from their multi-functional role in the context of their wider landscape (Nordregio 2004). With an increasing demand for forest products and ES (European Commission 2013), the loss of ecosystem functions in mountain areas increases the environmental risks in both mountains and adjacent lowland areas (Sampson et al. 2005). While traditional silvicultural systems (e.g. shelterwood, clear cutting and coppice) were developed focusing on sustainable timber production (Mathews 1999; Nyland 2002), sustainable forest management is the key concept that fosters the multi-functional role of forests. However, the integrative concept of multi-purpose forestry is challenging, due to its numerous and simultaneous conflicting objectives (Diaci et al. 2011). The single tree selection system, also known as continuous cover forestry, seems to be an appropriate silvicultural approach for integrating the multi-functional aspects of forest management (FM), especially in terms of environmental and social dimensions, but yet difficult to apply and debatable in terms of technological feasibility and economic efficiency (Axelsson and Angelstam 2011; Laiho et al. 2011; Thurner et al. 2011). There is a growing interest for close-to-nature silviculture, multiple-use forestry and adaptation of FM to climate change (Brang et al. 2014) on one hand, and an increasing demand of quality timber and a strong competition for energy wood (Sampson et al. 2005; Pepke 2007; Steirer et al. 2007) on the other hand. In this context, selection of harvesting systems (HS) for timber production represents a complex decision problem due to its numerous constraints with direct influence on the entire wood supply chain, the environment and the local communities. The need for corporate social responsibility in the forest sector (e.g. safety and health at work and environmental protection) by involving all relevant stakeholders (e.g. forest owners, forest enterprises, forest contractors, local communities, authorities and non-governmental organizations) in decision making is acknowledged and represents an important topic in the modern FM (Gordon et al. 2012; Matilainen 2013). Thus, the decision of selecting the

Adrian Enache adrian.enache@boku.ac.at

Timber felling and processing productivity (observed).

Country	Method	Operation	Productivity	Cost	Source
Spain	Chainsaw (CTL;TH)	Felling	2.2 $m^3\ h^{-1}$	10.0 € m^{-3}	Laina et al. (2013)
Croatia	Chainsaw (TH)	Felling and processing	4.3 $m^3\ h^{-1}$	2.1 € m^{-3}	Zečič and Marenč (2005)
Romania	Chainsaw (TH)	Felling	8.4 $m^3\ h^{-1}$	N/A	Borz et al. (2013)
Austria	Harvester	Felling & processing	18.8 $m^3\ h^{-1}$	7.5 € m^{-3}	Kühmaier and Stampfer (2012)
Spain	Harvester (CTL;TH)	Felling & processing	1.6 $m^3\ h^{-1}$	46.9 € m^{-3}	Laina et al. (2013)
Spain	Harvester (CTL;TH)	Felling & processing	6.7 $m^3\ h^{-1}$	11.1 € m^{-3}	Tolosana et al. (2014)
Sweden	Harvester (RF)	Felling & processing	23.8 $m^3\ h^{-1}$	N/A	Eriksson and Lindroos (2014)
Finland	Harvester (RF)	Felling & processing	30.0 $m^3\ h^{-1}$	N/A	Nurminen et al. (2006)
Slovakia	Harvester (RF)	Felling & processing	18.5 $m^3\ h^{-1}$	N/A	Slamka and Radocha (2010)
Ireland	Harvester (RL)	Felling & processing	37.0 $m^3\ h^{-1}$	2.9 € m^{-3}	Jirousek et al. (2007)
Sweden	Harvester (TH)	Felling & processing	11.3 $m^3\ h^{-1}$	N/A	Eriksson and Lindroos (2014)
Finland	Harvester (TH)	Processing	13.7 $m^3\ h^{-1}$	11.5 € m^{-3}	Petty and Kärhä (2014)
Finland	Harvester (TH)	Felling & processing	12.0 $m^3\ h^{-1}$	N/A	Nurminen et al. (2006)
Slovakia	Harvester (TH)	Felling & processing	6.8 $m^3\ h^{-1}$	N/A	Slamka and Radocha (2010)
Slovakia	Harvester (TH)	Felling & processing	5.2 $m^3\ h^{-1}$	N/A	Slugen et al. (2014)
Spain	Harvester (WT;TH)	Felling & bunching	5.3 $m^3\ h^{-1}$	14.1 € m^{-3}	Laina et al. (2013)

Note: TH – thinning; RF – regeneration felling; WT – whole tree harvesting system; CTL – cut-to-length.

appropriate HS becomes even more challenging. There are a number of factors that influence the selection, the utilization rates and the efficiency of HS in mountain forests, but the most important are the technical limitations, the social and environmental compatibility and the cost effectiveness of the systems (Holzleitner et al. 2011).

Levers et al. (2014) revealed that about 60–65% of the net annual forest growth was harvested in Europe in the las decade, with a high variability of harvesting intensities across Europe. The most influencing factors were: the tree species, the country specific characteristics (e.g. policies, socio-economic and cultural differences, and forest ownership structure), the terrain topography, the growing stock, the forest cover, the accessibility and the rotation period. Northern European countries mostly use fully mechanized HS (i.e. harvesters and forwarders), while in south-western and central Europe the combination of motor-manual felling and mechanized extraction (i.e. forwarders, skidders and cable yarders) are predominant, though with an increasing share of fully mechanized systems; eastern European countries have a lower degree of mechanization (Berg et al. 2012, 2014; Spinelli et al. 2013). Fully mechanized systems can be more productive and more cost effective then partly mechanized ones. They may also produce more timber over a fixed period with positive effects in high value creation and in establishing additional jobs in the wood supply chain. It is common that fully mechanized systems are also more ergonomic and safer than partly mechanized ones (Albizu-Urionabarrenetxea et al. 2013).

Productivity and costs of logging operations vary considerably across European countries, depending on different factors (i.e. terrain topography, method of harvesting, degree of mechanization, type of machinery and extraction distance (ED)). For felling and processing trees, literature reveals productivity rates of about 5 $m^3\ h^{-1}$ for partly mechanized systems and about 15 $m^3\ h^{-1}$ for fully mechanized systems (Table 1). In timber extraction, productivity may vary between 2.6 and 21.9 $m^3\ h^{-1}$ depending on the extraction technology used (Table 2).

Productivity has not only a direct economic impact, but also an environmental and social dimension, since it is linked with the energy requirements, the level of greenhouse gas emissions and the employment rate (Whittaker et al. 2011; Berg et al. 2012; Klvač et al. 2012; Vusić et al. 2013). In addition, the incidence of accidents in non-mechanized and partly mechanized loggings can be up to four times higher than in highly mechanized logging and the vast majority of accidents occur during felling trees with chainsaw, which is also the most frequent cause of fatal accidents in forestry (Potočnik et al. 2009; Lindroos and Burstrom 2010; Albizu-Urionabarrenetxea et al. 2013; Tsioras et al. 2014).

The selection of the appropriate HS is closely depending on the quality and the layout of the existing forest road networks (Kühmaier and Stampfer 2010; Enache et al. 2013). In addition, the geometric characteristics and the trafficability of the road network play an important role in timber transport efficiency (Svenson and Fjeld 2014). Depending on the minimum curve radius and the bearing capacity of the forest roads, either trucks or trucks with trailers can be used for transporting timber. The latter option is more efficient than the former in that higher payloads can be carried at lower fuel consumption rates per m^3.

Road density (RD) varies considerably across European countries depending on forest ownership, terrain topography, harvesting methods and extraction technologies available: 38.3 m ha^{-1} in Austria (Ghaffariyan et al. 2010a); 18.6 m ha^{-1} and 25.0 m ha^{-1} in Slovenia (Košir 2008; Mihelič and Krč 2009); 12.2 m ha^{-1} in Slovakia (Ambrušová et al. 2013); 15.6 m ha^{-1} in Croatia (Pentek et al. 2011) and 7.9 m ha^{-1} in Bulgaria (Yonov and Velichkov 2004). This can be explained by the different patterns (i.e. valley roads or slope roads) and country specific characteristics for developing forest road networks (e.g. know-how and financial schemes). The optimum RD varies between 16.9 and 27.8 m ha^{-1} and the optimum ED varies between 120 and 350 m, depending on the extraction technology (Table 3). There is a wide variability of the EDs in European mountain forests depending on the quality of the road network, the extraction technology available and the local topographic conditions. In skidding operations, the mean ED varies between 250 and 1300 m (Robek et al. 2005; Borz et al. 2013, 2014; Vusić et al. 2013; Marceta et al. 2014). In forwarding operations, average distances between 250 and 400 m are a good practice (Ghaffariyan et al. 2007; Laitila et al. 2007; Nurminen et al. 2006; Eriksson and Lindroos

Productivity in timber extraction (observed).

Country	Extraction method	ED (m)	Productivity (m^3 h^{-1})	Cost (€ m^{-3})	Source
Austria	Cable yarder (TH)	100	10.7	18.5	Ghaffariyan et al. (2009a)
Austria	Cable yarder (TH)	115	10.4	19.7	Ghaffariyan et al. (2010b)
Austria	Cable yarder (TH)	85	6.7	27.6	Ghaffariyan et al. (2010a)
Austria	Cable yarder (TH)	100	7.0	20.5	Ghaffariyan et al. (2009a, 2009b)
Austria	Forwarder	100	17.9	6.7	Ghaffariyan et al. (2007)
Finland	Forwarder	410	12.3	N/A	Nurminen et al. (2006)
Slovakia	Forwarder	1067	10.8	N/A	Slamka and Radocha (2010)
Finland	Forwarder (a) (TH)	250	7.1	N/A	Laitila et al. (2007)
Finland	Forwarder (b) (TH)	250	11.9	N/A	Laitila et al. (2007)
Spain	Forwarder (CTL; TH)	510	12.2	5.0	Laina et al. (2013)
Spain	Forwarder (CTL; TH)	N/A	14.9	3.1	Tolosana et al. (2014)
Ireland	Forwarder (RF)	500	16.0	4.5	Jirousek et al. (2007)
Sweden	Forwarder (RF)	420	21.4	N/A	Eriksson and Lindroos (2014)
Sweden	Forwarder (TH)	420	12.9	N/A	Eriksson and Lindroos (2014)
Spain	Forwarder (WT; TH)	170	10.5	5.8	Laina et al. (2013)
Italy	Horse (TH)	173	1.73	15.4	Magagnotti and Spinelli (2011)
Romania	Horse	300	2.6	N/A	Borz et al. (2013)
Bosnia & Herzegovina	Skidder	250	7.5	5.4	Marceta et al. (2014)
Croatia	Skidder	250	12.0	2.2	Sabo and Porsinsky (2005)
Italy	Skidder	140	4.8	16.7	Spinelli et al. (2012)
Romania	Skidder (RF)	1040	12.7	N/A	Borz et al. (2014)
Croatia	Skidder (RF)	260	4.9	N/A	Vusic et al. (2013)
Croatia	Skidder (RF)	210	3.2	N/A	Vusic et al. (2013)
Romania	Skidder 50Kw (SL)	870	5.6	N/A	Borz et al. (2013)
Romania	Skidder 68Kw (SL)	980	7.7	N/A	Borz et al. (2013)
Slovenia	Tractor	400	4.1	16.5	Zeljko and Jurij (2005)
Italy	Tractor (TH)	206	2.3	24.9	Magagnotti and Spinelli (2011)
Italy	Tractor (crawler)	120	3.6	25.7	Spinelli et al. (2012)

Note: (a) – manual felling; (b) – mechanized felling; TH – thinning; RF – regeneration felling; SL – salvage logging; WT – whole tree harvesting system; CTL – cut-to-length.

2014), while in cable yarding, average EDs of 300 m are common in Austria (Ghaffariyan et al. 2009a, 2010a; Kanzian 2003; Stampfer et al. 2003).

In this context, the aim of this study was to assess the current logging practices in European mountain forests, to highlight the existing efficiency gaps and to identify opportunities for increasing efficiency in timber production, focusing on the technical, economic, environmental and social aspects.

The study was conducted in seven case study areas (CSAs) which are characterized by distinct biophysical and governance environments. The CSAs are located in the main European mountain ranges which cover the most important forest types in Europe: Iberian Mountains (CSA 1), French Alps (CSA 2), Austrian Alps (CSA 3), Dinaric Mountains (CSA 4), Scandinavian Mountains (CSA 5), Western Carpathians (CSA6) and Rhodope Mountains (CSA 7). The main characteristics of the CSAs are presented in Tables 4 and 5. The top five tree species across CSAs are: spruce (39%), scots pine (11%), larch (11%), beech (10%) and fir (8%).

The CSAs were selected so that they cover a wide range of forest types, socio-economic conditions and cultural contexts of the European mountain forests, in order to reflect as much as possible the diversity of environmental conditions, tree species, demands for ES and related management goals of the forest owners. Thus, each selected CSA had to allow performing analysis at different spatial levels: an administrative district as the largest level, a functional unit representing the FM unit, a small catchment area and the forest stand level.

A web-designed data collection protocol (questionnaire) was developed and sent to the case study responsible persons (CSRPs) of each CSA for gathering data about harvesting technologies and systems in January 2013. The questionnaires were accompanied by a manual for data input, including a thorough operational description of the procedures for data

Ranges of optimum road spacing, RD and ED.

Method of timber extraction	ORS (m)	ORD (m ha^{-1})	OED (m)	Source
Cable yarder (uphill)	261	38.3	150	Ghaffariyan et al (2010a)
Cable yarder (uphill and downhill)	373	26.8	105	Ghaffariyan et al (2010a)
Cable yarder (uphill)	329	30.4	125	Ghaffariyan et al (2010b)
Cable yarder (uphill and downhill)	474	21.1	90	Ghaffariyan et al (2010b)
Forwarder	463	21.6	285	Ghaffariyan et al. (2009b)
Forwarder	641	15.6	320	LeBel et al. (2003)
Horse skidding	520	19.2	260	Soom (1950)
Skidder	330	30.3	165	Heinimann (1998)
Skidder	630	15.9	315	Peters (1978)
Skidder	1115	9.0	558	Ghaffariyan and Sobhani (2008)
Skidder	275	36.4	138	Thompson (1992)
Cable yarder	360	27.8	120	(indicative mean)
Forwarder	550	18.2	300	(indicative mean)
Skidder	590	16.9	350	(indicative mean)

Note: ORS – optimum road spacing; ORD – optimum road density; OED – optimum ED.

General overview of the case study areas.

CSA	Location	Forest area (ha)	Altitude (m) min	Altitude (m) max	Altitude (m) mean±SD	Slope (%) min	Slope (%) max	Slope (%) mean±SD	Tree species	ES
CSA 1	Valsain, Spain	2654	1163	1941	1422 ± 107	0	136	32 ± 21	Scots pine, Pyrenean oak	TP, CS, NC, REC
CSA 2	Vercors, France	5190	560	2258	1310 ± 189	0	242	36 ± 25	Spruce, fir, beech	TP, BMfE, PF, NC
CSA 3	Montafon, Austria	579	1069	1916	1523 ± 157	0	152	61 ± 21	Spruce, beech, maple, fir	TP, PF, NC, GM
CSA 4	Sneznik, Slovenia	5016	614	1765	973 ± 201	0	82	22 ± 14	Beech, fir, spruce	TP, GM, NC, PF
CSA 5	Vilhelmina, Sweden	10,405	342	669	482 ± 68	0	71	11 ± 7	Scots pine, spruce, birch	TP, CS, NC
CSA 6	Vikartovce, Slovakia	5130	682	1545	1057 ± 166	0	78	29 ± 14	Spruce, fir, beech	TP, NC, REC, PF
CSA 7	Shiroka Laka, Bulgaria	1737	892	2177	1580 ± 176	0	397	56 ± 52	Scots/black pine, fir, beech, spruce	TP, BMfE, CS, NC, PF

*Note: TP = timber production; CS = carbon sequestration; NC = nature conservation; REC = recreation; BMfE = biomass for energy; PF = protective function (e.g. rockfall, avalanches, flooding, erosion, water resources); GM = game management.

Geological characteristics and FM systems across CSAs.

CSA	Bedrock	Soil Type	Soil Depth (cm)	Soil WSC (mm)	Share of FM systems (%) Coppice	EA	UEA	no FM
CSA 1	A	cambisol	60–100	61–195	59	35	–	6
CSA 2	C	Cambisol, leptosol, umbrisol	N/A	30–90	–	–	94	6
CSA 3	A, M	Cambisol, ranker, Podzol	35–60	130–250	–	–	100	–
CSA 4	C	Cambisol, leptosol	15–30	60–100	–	29	65	6
CSA 5	A	Podzol, umbrisol, arenosol	10–40	50–325	–	100	–	–
CSA 6	A, C	Cambisol, podzol, rendzina	35–55	100–170	–	100	–	–
CSA 7	A, C, M	Cambisol, rendzina	40–80	80–220	–	70	–	30

Note: Bedrock: A – acidic; C – calcareous; M – mixed; Soil type – the predominant soil type; WSC – water storage capacity; FM systems: EA – even-aged; UA – uneven-aged; no FM – no forest management applied.

Structure of the database at RL and RST level.

Road network and transport systems
Scale: RL

Road network	*Transport method*	*Transport factors*	*Accidents in logging operations*
Density roads (m ha^{-1})	Single truck	Loading capacity (t)	Accident quote
Density skid trails (m ha^{-1})	Truck with trailer	Transport distance (km)	Frequency in harvesting
Construction costs (€ m^{-3})	Train	Fuel costs (€ litre^{-1})	Frequency in extraction
Maintenance costs (€ m^{-3})	Others	Transport costs (€ m^{-3})	–

Harvesting technologies
Scale: RST

Harvesting method	*Felling*	*Delimbing*	*Bucking*	*Productivity*	*Costs*
Whole tree (WT)	Axe	Axe	Saw	m^3 PSH^{-1}	€ m^{-3}
Tree-length (TL)	Saw	Saw	Chainsaw		
Cut-to-length (CTL)	Chainsaw	Chainsaw	Processor		
	Feller buncher	Feller buncher	Harvester		
	Harvester	Processor	–		
	–	Harvester	–		

Extraction technologies
Scale: RST

Extraction methods	*Distance*	*Productivity*	*Costs*
Manual			
Animal			
Tractor	m	m^3 PSH^{-1}	€ m^{-3}
Skidder			
Forwarder			
Cable yarder			

collection, definition of terms, details about the structure of the questionnaire and linker functions (Klopcic et al. 2013). The CSRPs were local forest researchers in charge with project coordination in each CSA. CSRPs had to fill in the data regarding the logging operations performed between November 2012 and May 2013 in their corresponding CSA. The main purpose of the questionnaire was to gather data for a broader analysis of the current FM practices (i.e. silvicultural treatments) and only secondly data about logging operations.

The focus of data collection was set on two different scales: the *representative landscape* (RL) scale, for collecting more general data about the road network and transport systems, and the *representative stand type* (RST) scale, for collecting more detailed data about HS (Table 6). The RSTs are spatial entities defined by species mixture, stand development stage, stand structure and site type; the site types describe the local site conditions such as altitude, climate, geology and soil characteristics. RLs are spatially explicit entities that go beyond the stand scale and they represent typical

Degree of mechanization of the HS.

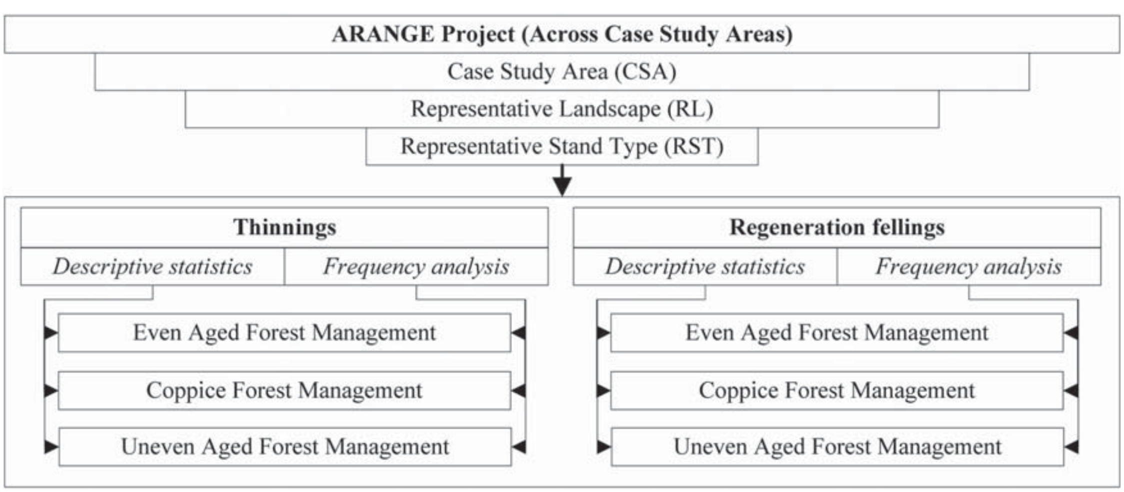
Operation	Means of execution	Non-mechanized	Partly mechanized	Highly mechanized	Fully mechanized
Felling and processing	Saw/Axe	X	-	-	-
	Chainsaw	-	X	X	-
	Processor	-	-	X	-
	Harvester	-	-	-	X
Extracting	Manual	X	X	-	-
	Animal	X	X	-	-
	Tractor	-	X	X	-
	Skidder	-	X	X	-
	Forwarder	-	X	X	X
	Cable Yarder	-	X	X	-

Note*:* X = required; - = not required.

conditions within the specific CSAs (Lexer 2013). Eight *business-as-usual* (BAU) FM systems were defined according to Mathews (1999) and Nyland (2002) covering the entire rotation period of the forest stands: *even-aged, two-aged, uneven-aged (UA), coppice, short rotation, agro-forestry, transformation* and *no management*, respectively. However, only even-aged (EA), UA, coppice and no management FM systems were actually reported in CSAs. The questionnaires were divided into three main parts: (i) input of the identification data (e.g. ID case study area; ID of RST and ID of RL); (ii) input of data in a particular RST or RL; (iii) viewer of the data in a particular RST (with possibility to edit). Due to increased level of detail of the required data and the country specific characteristics in each CSA, it was not possible to collect all type of the requested data about logging operations in every CSA. This was the case in both RL and RST scales.

The analysed parameters (Table 6) were defined and described by Leitner et al. (2013). The productivity referred to productive system hours including delays of 15 minutes (PSH_{15}), the system costs were calculated using the Food and Agriculture Organization of the United Nations (FAO) cost calculation scheme adapted by Holzleitner et al. (2011). There is no standardized definition of the forest roads in Europe. In some regions, the definition of forest roads includes the unpaved roads and the skid roads (i.e. Slovakia; Ambrušová et al. 2013), while in others, especially in Scandinavia, seasonal and permanent forest roads are reported (Olsson 2005; Statistics Norway 2009). The definition of forest roads used in this study refers to roads within the boundaries of the CSAs that are trafficable by trucks with or without trailers. The mean ED in each CSA was the mean value calculated from the EDs reported in each RST of that CSA. The mechanization degrees are described in Table 7. The following harvesting methods were defined: WT – whole-tree (only felling before extraction); TL – tree-length (felling and delimbing before extraction); CTL – cut-to-length (felling, delimbing and bucking before extraction). HS are the means (i.e. manual, animals or machinery) used for felling, processing and extracting timber from the stand to the forest road.

Since the data were not collected for the main purpose of comparing timber harvesting practices at RST level, this study lacked an experimental design that could allow a more analytic approach of the datasets analysis. There were no time studies conducted in this study, but only empirical data collection from executed logging operations by forest contractors. Therefore, the findings of this study should be considered as indicating trends and not as standard or fix values for a specific FM system, type of felling or RST. Nonetheless, this shortcoming was balanced by performing descriptive statistics (Figure 1) of the collected data, which were reported separately for thinning and regeneration felling operations per each CSA, RL and RST (Leitner et al. 2013).



Structure of HS data analysis.

The minimum, maximum, mean and standard deviations of the following indicators were determined at RST level: *harvesting productivity*, *harvesting cost, ED, extraction productivity and extraction cost*. In addition, the frequency of occurrence of the following parameters was analysed: *degree of mechanization*, *harvesting method* and *extraction method*. At RL level the following parameters were analysed: *transport systems,* RD, *and road construction* and *maintenance costs*. In the end, the data were compiled at CSA level and statistical analyses were performed in PASW® Statistics 18 using a significance level $\alpha = 5\%$. Student's *t*-test was used to test the differences between two groups and ANOVA for testing within group variability and differences between three or more groups. Pearson's and Spearman's coefficient were used to test the correlation between two groups, as they are appropriate for continuous, discrete and ordinal variables (Lehman et al. 2005).

For assessing HS performance and identifying the efficiency gaps in timber harvesting, three scenarios were defined:

- *Scenario 1: BAU* – considers current infrastructure conditions and currently used HS;
- *Scenario 2: Optimum_ED_BAU_HS* – considers the indicative optimum ED for the currently used HS (BAU HS) and optimum productivity of BAU HS. This hypothesis means the road network has to be extended for reaching the optimum ED for BAU HS.
- *Scenario 3: Optimum_ED_NEW_HS* – considers the indicative optimum ED for the share of technically feasible state-of-the-art (new) HS in each CSA. This hypothesis means the road network has to be extended for reaching the optimum ED for state-of-the-art (new) HS.

The following performance indicators were analysed: RD (m ha^{-1}), *ED* (m), *transport efficiency* (%), *productivity* (m^3 PSH$_{15}^{-1}$), *cost* (€ m^{-3}), *fuel consumption* (l m^{-3}), *accidents rate* (number per million m^3), *CO_{2eq} emissions* (kg m^{-3}) and *mean damage stand index* (%). The indicator values from Scenario 1 (BAU) were compared with the benchmark values (desired optimum state) from Scenario 2 and Scenario 3.

The optimization of forest road networks strongly depends on local terrain, economic, machinery and social conditions and there is no single formula that can be used for determining the optimum layout (Heinimann 1998; Sessions and Boston 2006; Contreras and Chung 2007). In Scenarios 2 and 3, the indicative optimum values for RD and ED were calculated for cable yarders, forwarders and skidders based on road spacing optimization models existing in literature which used the total road and harvesting cost minimization approach (see Table 3). The performance of the other HS indicators was calculated based on RD and ED values. The CO_{2eq} emissions were determined using a stoichiometric combustion model (Heinimann 2012) for a net calorific value of diesel engines of 42.76 MJ/kg (Stanescu 2012) and the diesel density of 0.835 kg m^{-3} (Berg and Karjalainen 2003). The transport efficiency was determined by dividing the total weight of the loaded trucks to the maximum allowable weight reported in each CSA. The input data used in calculations are depicted in Table 8. The system costs reported in this table were used only for CSAs that did not report their local HS system costs.

Input data for efficiency gap analysis of HS.

Parameter	CSW	HV	AN	TR	SKD	FW	CY
Fuel consumption (l/h)	1.5	15.6	0	7.5	12.5	13.9	13.3
Accidents (n/mill. m^3)	75	11	75	12	12	11	36
CO_{2eq} emissions (kg/h)	3.5	53.4	0.3	19.8	33	36.3	35.6
Mean damage stand index (%)	16	8.5	5.6	11.5	11.5	2.5	29
Cost (€/h)	40	157	40	64	84	101	200

Sources: Fuel consumption (Kastner 2014); Accidents (Jänich 2011; Kastner 2014; Tsioras et al. 2011); CO_{2eq} emissions (calculated after: ***Berg and Karjalainen 2003; Heinimann 2012; Stanescu 2012); Stand damage (Limbeck-Lilienau 2004; Raab et al. 2002; Siren et al. 2015; Wirth and Wolff 2008); Cost (FAO scheme adapted after Holzleitner et al. 2011).
Note: CSW – chainsaw; HV – harvester; AN – animal; TR – tractor; SKD – skidder; FW – forwarder; CY – cable yarder.

For reporting and interpreting the results, the following procedure was defined: (i) describe the results of CSAs and highlight the impact on technical feasibility, economic efficiency, environmental and social dimensions; (ii) perform statistical analysis and comparisons with best practice examples from literature; (iii) identify gaps and suggest recommendations.

Twelve RLs and 193 RSTs were identified across CSAs. The analyses presented below were based on the number of forest operations carried out and not on the volume of timber harvested, because the harvest volume per RST for most of the CSAs was not available. CSA4 was not included in the analysis of forest infrastructure and timber transport due to lack of data availability.

A significant variability of the road network densities was noticed across CSAs (Table 9; ANOVA, df = 5; $F = 18.48$; Sig. = 0.008), from 7.0 m ha^{-1} in Sweden (CSA5) to 34.7 m ha^{-1} in Spain (CSA1). The high road densities in CSA1 and CSA7 might be explained by the inclusion of public roads in calculations and by the correlation with the increased risk of forest fires in these areas. The average RD was 18.5 m ha^{-1}, which is a low figure even for mountain forests. The share of the forest roads suitable for trucks with trailers (T&T) played an important role in the equation of RD. Spain (CSA1) reported the

Characteristics of the forest road network.

Indicator	CSA1	CSA2	CSA3	CSA5	CSA6	CSA7	Mean
Forest RD (m ha^{-1})	34.7	14.3	19.2	7.0	9.5	26.3	18.5
– of which trafficable for T&T	18.0	14.3	11.4	7.0	4.5	11.9	11.2
– of which trafficable for trucks	16.6	0.0	7.7	0.0	5.0	14.4	7.3
Construction cost (€ m^{-1})	20.0	35.0	95.0	20.0	39.0	25.0	39.0
Maintenance cost (€ m^{-1} year^{-1})	0.8	0.1	2.5	0.1	7.4	0.1	1.8

Note: T&T – truck with trailer.

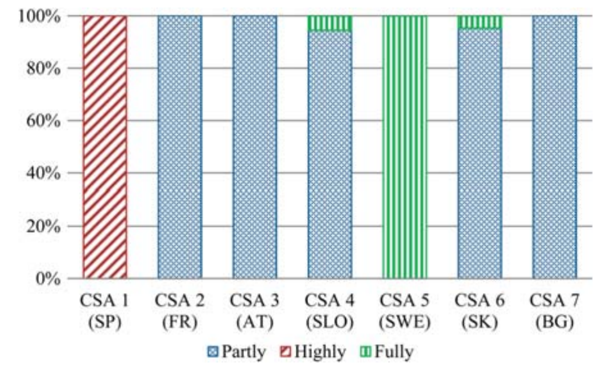
highest density of T&T roads (18.0 m ha^{-1}), while Slovakia (CSA6) reported the lowest amount (4.5 m ha^{-1}).

The costs of the road networks vary considerable across CSAs. The mean road construction cost was 39.0 € m^{-1} (min = 20.0; max = 95.0; SD = 24.1; Table 9). The road construction costs depend on a number of factors, such as terrain topography, geomorphological layer, road width and road grade, longitudinal transport of material, streams crossings (culverts, fords and bridges), gravel pavement requirements and availability, slope stabilization requirements, machinery and labour costs. The higher costs in CSA3 were caused by the steeper and stonier terrain that required stone excavation, drilling, blasting and longitudinal transport of raw material. The mean road maintenance cost across CSAs was 1.8 € m^{-1} year^{-1} (min = 0.1; max = 7.4; SD = 2.4). Literature shows variable maintenance costs across Europe (e.g. 0.6 € m^{-1} in Croatia, 1.0 € m^{-1} in Italy and 3.5 € m^{-1} in Austria; Pentek et al. 2005; Ghaffariyan et al. 2009b; Pellegrini et al. 2013). The maintenance costs are usually higher for valley roads than for slope roads and they increase with the slope gradient and decreasing soil bearing capacity (Heinimann 1998; Enache and Stampfer 2015). The most expensive road maintenance costs were reported in CSA6 and they suggest the poor quality of the road network.

The mean loading capacity of the timber trucks was 22.2 tonnes (Table 10) with significant variations across CSAs (ANOVA, df = 5; F = 27.85; Sig. = 0.003). The mean timber transport cost was 9.1 € m^{-3}, with significant variations across CSAs (ANOVA, df = 5; F = 20.65; Sig. = 0.006). Sweden (CSA5) reported the highest transport costs (18.0 € m^{-3}), while Slovakia (CSA6) and Bulgaria (CSA7) the lowest costs (4.0 € m^{-3} and 6.0 € m^{-3}, respectively). Pearson's coefficient showed a significant correlation between the transport costs and transport distance (ρ = 0.869; Sig. = 0.025), and between load capacity and maximum allowed load (ρ = 0.881; Sig. = 0.020). Indeed, the transport distance in Sweden was about 260 km while in Slovakia and Bulgaria only about 40 km. In addition, the cheap labour and the low system costs are other causes of the lower transport costs in CSA6 and CSA7. There was no significant correlation between the load capacity of the vehicles and the transport costs, although Pearson's coefficient (ρ = 0.697; Sig. = 0.124) suggests that transport cost was influenced by the load capacity. Table 10 shows efficiency gaps in timber transport in the same CSAs which reported a lower share of roads trafficable for trucks with trailers (see Table 9), which suggests that the quality of the road networks (e.g. geometric characteristics and pavement structure) should be improved in these CSAs for increasing the transport efficiency.

Performance of transport systems.

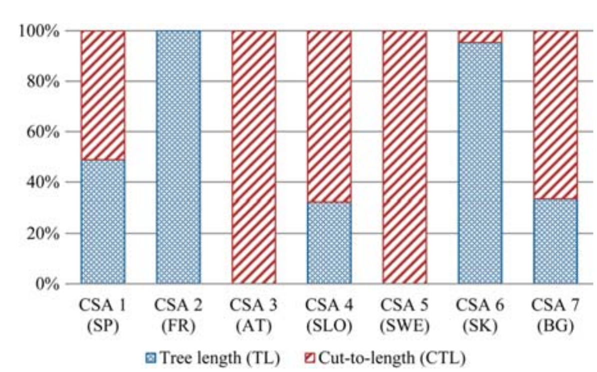
Indicator	CSA1	CSA2	CSA3	CSA5	CSA6	CSA7	Mean
Load capacity (t)	19.7	32.4	12.1	36.5	20.9	11.6	22.2
Empty vehicle weight (t)	18.0	20.5	16.4	20.5	20.5	16.0	18.7
Total weight of loaded truck (t)	37.7	52.9	28.5	57.0	41.4	27.6	40.9
Max. allowed weight (t)	40	48	42	50	40	40	43
Efficiency gap (%)	−6%	10%	−32%	14%	4%	−31%	−7%
Transport distance (km)	100	50	50	260	40	50	92
Transport cost (€ m^{-3})	7.0	10.0	9.6	18.0	4.0	6.0	9.1



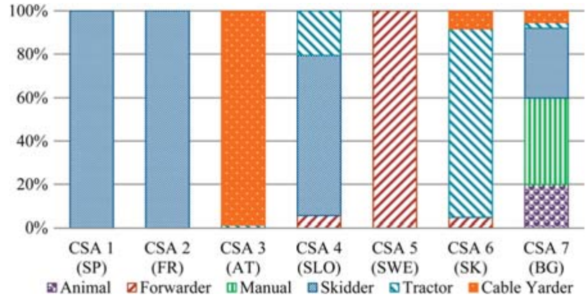
Degree of mechanization of HS.

CSA5 (Sweden) reported exclusively fully mechanized HS, CSA1 (Spain) reported only highly mechanized systems, while the other CSAs reported mainly partly mechanized systems (Figure 2). There was no significant correlation between the mechanization degree and the harvesting method (*Pearson's coef.* ρ = 0.448; Sig. = 0.313), nor between the FM system applied and the mechanization degree (*Pearson's coef.* ρ = −0.237; Sig. = 0.609). The tree-length (TL) method was used in 60% of the analysed forest operations, while CTL was used in 40% of the cases (Figure 3). The FM system did not influence the selection of the harvesting method applied (*Pearson's coef.* ρ = 0.005; Sig. = 0.991).

Skidding was the most common extraction method across CSAs (Figure 4). There was no significant correlation between the average slopes and the extraction methods used in each CSA (*Pearson's coef.* ρ = 0.115; Sig. = 0.829). This was rather surprising, since it seems the technical limitation of machinery was not a decisive criterion in selecting the appropriate extraction technology. Though, Austria (CSA3) and Sweden (CSA5) represent best practice examples for



Share of harvesting methods by CSA.



Share of extraction methods by CSA.

Extraction methods by type of felling and FM system.

	Share by type of felling (%)			
	Thinnings		Regeneration fellings	
Extraction method	Even-aged	Uneven-aged	Even-aged	Uneven-aged
Animal	2%	–	2%	–
Forwarder	15%	–	12%	–
Manual	10%	–	–	–
Skidder	7%	76%	25%	33%
Tractor	66%	24%	60%	–
Cable yarder	–	–	1%	67%
Total	100%	100%	100%	100%

using the appropriate extraction technology according to the local slope conditions.

If the cable yarding technology was not available for steep terrain harvesting, which was the case in many CSAs (Figure 4), harvesting operations were usually performed with inappropriate technology. Tractors and skidders were used in 75% of the analysed forest operations, while cable yarders and forwarders only in 15%, respectively 8% of the cases.

Table 11 reveals that no forwarders were used for extracting timber in UA forests, where extraction was performed entirely with tractors and skidders in thinnings and with skidders (33%) and cable yarders (67%) in regeneration fellings. In EA stands, no cable yarders were used in thinnings, while skidding with tractors was the dominant extraction method (66%), followed by forwarding (15%). In EA regeneration fellings, extraction with tractors was the most common extraction method (60%), followed by skidders (25%) and forwarders (12%). Although no significant correlation was found between the extraction methods and the FM systems applied in CSAs, Pearson's coefficient ($\rho = 0.657$; $p = 0.156$) suggests that skidders are used in EA and UA stands, while forwarders are mostly used in EA forests and cable yarders in UA stands.

The mean ED across CSAs was 500.9 m (*min = 100.0*; *max = 1400.0*; SD = 122.3; Table 12). The mean ED was practically similar in thinning operations and regeneration fellings (*t*-test; $p = 0.054$). High EDs lead to long extraction time and high extraction costs. The higher mean ED in CSA6 (Slovakia) was caused by the very low density and poor quality of forest roads, which limits the effective use of forwarders and cable yarders (Ambrušová et al. 2013). In contrast, the low ED reported in CSA7 (Bulgaria) can be explained by the non-mechanized extraction methods, which are not effective for distances longer than 300 m (Gumus and Acar 2010; Borz and Ciobanu 2013).

Timber harvesting refers to tree felling, delimbing and bucking operations. The two latter operations were referred together as processing. The mean harvesting productivity across CSAs was 9.0 $m^3\,h^{-1}$ (min = *1.0*; *max = 26.0*; SD = 6.2; Table 13). The mean productivity in timber harvesting varied significantly across CSAs (ANOVA, df = 6; $F = 9.69$; Sig. = 0.021). The productivity was about 42% higher in regeneration fellings than in thinnings (*t*-test; $p = 0.075$) and consequently the harvesting costs were with about 26% lower in the former than in the latter case (*t*-test; $p = 0.065$).

The mean harvesting cost across CSAs was 11.1 € m^{-3} (*min = 3.0*; *max = 34.8*; SD = 7.1). The harvesting costs varied significantly across CSAs (ANOVA, df = 6; $F = 23.54$; Sig. = 0.003). As such very expensive machines, harvesters proved to be cost-efficient, due to their high productivity (e.g. CSA 5). In contrast, felling and processing with chainsaw was usually more expensive because of the low productivity. In CSAs where felling and processing was executed by chainsaw (CSA1; CSA3), the costs were higher than in fully mechanized systems (CSA5). Only in regions where the labour costs were low (CSA 6 and CSA 7), operating with chainsaw was an acceptable alternative.

The mean timber extraction productivity across CSAs was 10.2 $m^3\,h^{-1}$ (min = 1.0; max = 26.0; SD = 9.3; Table 14). The mean productivity varied significantly across CSAs (ANOVA, df = 6; $F = 21.69$; Sig. = 0.006), from 2.3 $m^3\,h^{-1}$ in CSA 7 (Bulgaria) to 17.6 $m^3\,h^{-1}$ in CSA 5 (Sweden). The low productivity in CSA7 was caused by the utilization of non-mechanized extraction methods in a significant proportion (see Figure 4). The high productivity in CSA5 represents a good practice

Average ED by type of forest operation.

	Thinning operations					Regeneration fellings					Total operations				
CSA	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*
CSA1	498.8	400	900	116.0	51	553.0	400	900	176.8	33	520.1	400	772	139.9	84
CSA2	488.9	300	500	47.1	18	–	–	–	–	–	488.9	300	500	47.1	18
CSA3	–	–	–	–	–	494.5	100	500	46.6	71	494.5	100	500	46.6	71
CSA4	428.8	350	650	56.4	57	470.7	350	650	69.4	39	445.8	350	650	61.7	96
CSA5	400.0	400	400	0.0	15	400.0	400	400	0.0	15	400.0	400	400	0.0	30
CSA6	572.6	100	1400	300.4	146	567.9	100	1400	299.9	145	570.3	100	1400	300.2	291
CSA7	176.7	150	300	51.8	21	215.1	150	300	39.8	21	195.9	150	300	45.8	42
TOTAL	493.5	100	1400	136.8	308	508.0	100	1400	130.1	324	500.9	100	1400	122.3	632

Productivity and costs of timber harvesting across CSAs by type of felling.

		Thinning operations					Regeneration fellings					Total operations				
Indicator	CSA	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*
Productivity ($m^3\ h^{-1}$)	CSA1	1.0	1.0	1.0	0.0	51	1.7	1.0	2.0	0.7	33	1.3	1.0	2.0	0.5	84
	CSA2	3.0	3.0	3.0	0.0	18	–	–	–	–	–	3.0	3.0	3.0	0.0	18
	CSA3	–	–	–	–	–	4.0	4.0	4.0	0.0	71	4.0	4.0	4.0	0.0	71
	CSA4	10.9	4.0	15.0	4.2	57	15.9	15.0	16.0	0.1	39	12.9	4.0	16.0	2.6	96
	CSA5	9.0	9.0	9.0	0.0	15	24.3	21.0	26.0	1.5	15	16.6	9.0	26.0	0.8	30
	CSA6	9.6	5.0	14.0	2.8	146	14.0	14.0	14.0	0.0	145	11.8	5.0	14.0	1.4	291
	CSA7	1.5	1.0	9.0	2.0	21	2.1	2.0	3.0	0.2	21	1.8	1.0	9.0	1.1	42
TOTAL		7.4	1.0	15.0	4.5	308	10.5	1.0	26.0	9.2	324	9.0	1.0	26.0	6.2	632
Cost (€ m^{-3})	CSA1	31.2	29.0	32.4	2.4	51	12.9	7.6	25.0	12.3	33	24.0	7.6	32.4	11.0	84
	CSA2	12.0	12.0	12.0	0.0	18	–	–	–	–	–	12.0	12.0	12.0	0.0	18
	CSA3	–	–	–	–	–	20.0	20.0	20.0	0.0	71	20.0	20.0	20.0	0.0	71
	CSA4	18.9	10.4	34.8	9.0	57	9.9	9.8	10.4	0.1	39	15.2	9.8	34.8	5.4	96
	CSA5	14.0	14.0	14.0	0.0	15	5.6	5.0	7.0	0.7	15	9.8	5.0	14.0	0.3	30
	CSA6	4.8	3.0	8.0	1.9	146	4.5	3.0	7.0	1.3	145	4.6	3.0	8.0	1.6	291
	CSA7	7.0	6.7	7.0	0.2	21	5.0	5.0	5.0	0.0	21	6.0	5.0	7.0	0.1	42
TOTAL		12.8	3.0	34.8	9.5	308	9.5	3	25	6.0	324	11.1	3.0	34.8	7.1	632

Productivity and costs of timber extraction by type of felling.

		Thinning operations					Regeneration fellings					Total operations				
Indicator	CSA	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*
Productivity ($m^3\ h^{-1}$)	CSA1	7.9	4.0	10.0	4.2	51	8.6	8.0	10.0	1.4	33	8.2	4.0	10.0	2.8	84
	CSA2	10.0	10.0	10.0	0.0	18	–	–	–	–	–	10.0	10.0	10.0	0.0	18
	CSA3	–	–	–	–	–	8.0	6.0	8.0	0.2	71	8.0	6.0	8.0	0.2	71
	CSA4	26.7	15.0	35.0	8.1	57	37.6	35.0	38.0	0.4	39	31.1	15.0	38.0	5.0	96
	CSA5	11.0	11.0	11.0	0.0	15	24.3	21.0	26.0	1.5	15	17.6	11.0	26.0	0.8	30
	CSA6	9.3	1.0	14.0	3.2	146	14.0	14.0	14.0	0.0	145	11.6	1.0	14.0	1.6	291
	CSA7	1.2	1.0	1.3	0.1	21	3.3	2.7	5.0	0.7	21	2.2	1.0	5.0	0.4	42
TOTAL		8.5	1.0	14.0	8.5	308 (251)	11.6	2.7	26.0	12.8	324 (285)	10.2	1.0	26.0	9.3	632 (536)
Cost (€ m^{-3})	CSA1	8.3	7.4	10.1	2.0	51	12.0	7.4	14.0	4.7	33	9.8	7.4	14.0	3.1	84
	CSA2	11.0	11.0	11.0	0.0	18	–	–	–	–	–	11.0	11.0	11.0	0.0	18
	CSA3	–	–	–	–	–	24.9	15.0	25.0	1.2	71	24.9	15.0	25.0	1.2	71
	CSA4	15.8	9.0	18.1	1.8	57	12.9	12.8	13.9	0.2	39	14.6	9.0	18.1	1.2	96
	CSA5	8.0	8.0	8.0	0.0	15	4.0	4.0	4.0	0.0	15	6.0	4.0	8.0	0.0	30
	CSA6	8.9	7.0	12.0	2.0	146	9.1	7.0	13.0	2.2	145	9.0	7.0	13.0	2.1	291
	CSA7	9.5	9.0	14.0	1.4	21	9.1	8.0	16.0	3.5	21	9.3	8.0	16.0	2.4	42
TOTAL		10.2	7.0	18.1	2.9	308	13.1	4	25	7.0	324	11.7	4.0	25.0	6.2	632

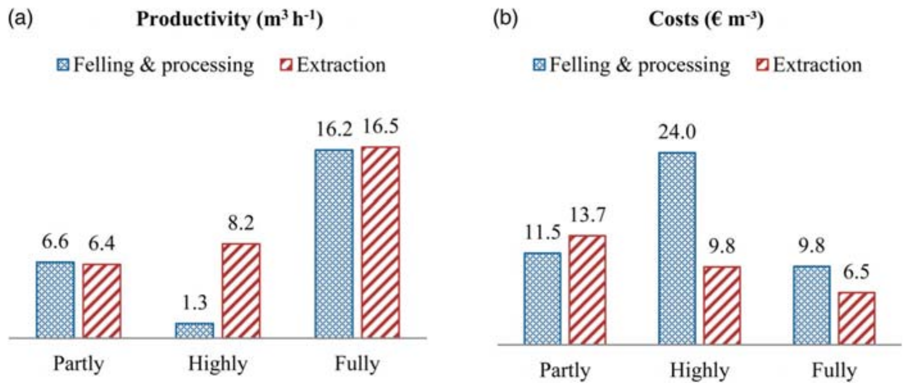
Note*:* In round brackets. the number of operations used for calculating the mean.

of applying CTL method and fully mechanized systems and can be used as benchmark value for timber forwarding on distances of 400 m. Thus, the very high productivity reported in CSA4 (31.1 $m^3\ h^{-1}$; Slovenia) was questionable when compared with literature (4.0 $m^3\ h^{-1}$; Zečič and Marenč 2005), especially when CSA4 reported that 95% of the timber was extracted by skidders and tractors on a distance of about 450 m. Hence, CSA4 was considered an outlier and excluded from further analysis. Surprisingly, the productivity reported in CSA 6 (11.6 $m^3\ h^{-1}$) was very good for extracting timber with tractors on distances of about 615 m.

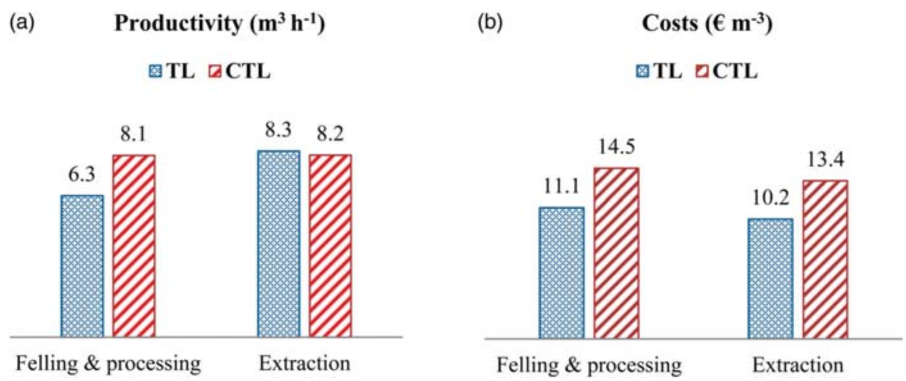
Table 14 reveals that extraction productivity in regeneration felling was about 36% higher than in thinning operations (*t*-test; $p = 0.063$), while the costs, surprisingly, were also about 28% higher, although not statistically proved (*t*-test; $p = 0.639$). In general, the extraction costs are higher when the ED is longer, the capacity of the vehicle is lower and the system (machine and operator) costs are higher. The average timber extraction cost across CSAs was 11.7 € m^{-3} (*min = 6.0*; *max = 25.0*; SD = 6.2). The extraction costs varied significantly across CSAs (ANOVA, df = 6; $F = 26.53$; Sig. = 0.002).

Figure 5 reveals a significant increase in productivity from partly to fully mechanized systems, both in felling and processing operations (*Spearman's coeff.* $\rho = 0.926$; Sig. = 0.008) and in timber extraction ($\rho = 0.698$; Sig. = 0.070). Though, in CSA1 (highly mechanized systems and coppice management) the productivity of felling and processing was lower than in partly mechanized systems. This was probably because of the smaller tree dimensions and the high waiting times between felling and processing, which also lead to higher harvesting costs. Felling and processing costs were about 15% lower in fully mechanized systems than in partly mechanized ones. Although statistics did not confirmed this trend, Spearman's coefficient ($\rho = -0.600$; $p = 0.208$) suggests that higher productivity leads to lower costs. Indeed, extraction costs were about 28% lower in highly mechanized systems and about 53% lower in fully mechanized systems than in partly mechanized systems.

The efficiency of logging operations varied with the harvesting method (Figure 6). The productivity of felling and processing was about 29% higher in CTL harvesting method than in TL method, but the costs were also about 30% higher in the



Efficiency by degree of mechanization.

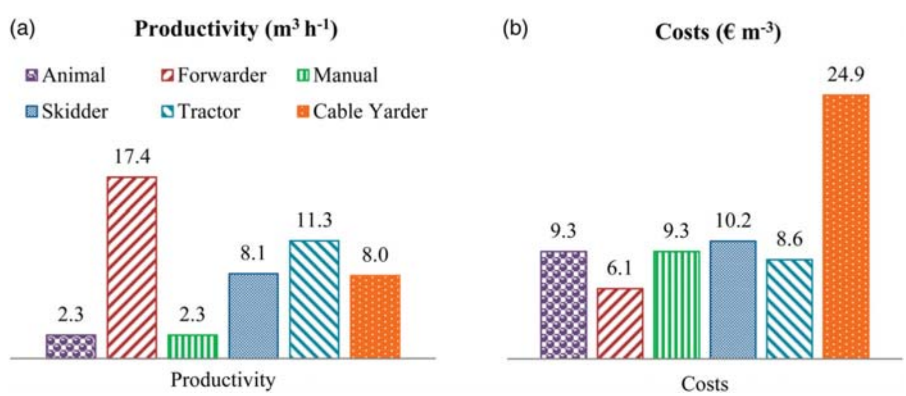


Efficiency in timber harvesting by harvesting method.

former than in the latter case. The extraction productivity was almost equal in CTL and TL methods, while the extraction costs were about 32% higher in CTL method than in TL method. This can be explained by the more expensive HS machinery used in CTL (usually the combination of harvester with forwarder, or chainsaw with cable yarders) than in TL method (usually chainsaw in combination with skidders), which can be seen as a cost for improved environmental performance and ergonomics of the logging operations.

The efficiency in timber extraction varied with the extraction method used (ANOVA, $df = 5$; $F = 12.4$; $Sig. = 0.017$). With increasing productivity, usually lower costs are expected. Spearman's coefficient ($\rho = -0.529$; $p = 0.280$) did not confirm this hypothesis, although the negative value suggests that the lower the productivity was the higher the costs were. Forwarding was the most efficient extraction method across CSAs, while non-mechanized systems reported the lowest productivity (Figure 7). Skidders and cable yarders reported almost equal productivities ($8.0\ m^3\ h^{-1}$), but the costs of cable yarding ($24.9\ €\ m^{-3}$) was much higher than any other extraction method. This is due to the high system costs of cable yarders.

Table 15 shows that FM systems had no significant influence on the mean ED (*Pearson's coef.* $\rho = -0.347$; $Sig. = 0.445$). The extraction productivity in coppice and EA FM was higher with 20% and respectively 30% than in UA



Efficiency of extraction methods.

ED productivity and costs of harvesting by FM system.

Indicator		Coppice management					Even-aged management					Uneven-aged management				
		Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*N*
Felling and Processing	Prod	1.0	1.0	1.0	–	43	10.3	1.0	26.0	8.9	445	7.3	3.0	16.0	6.7	144
	Cost	30.7	25.0	32.4	–	43	7.3	3.0	34.8	5.7	445	16.9	9.8	31.3	4.1-	144
Extracting	Prod	10	10	10	––	43	10.6	1.0	26.0	6.7	404	8.4	6.0	10.0	1.4	89
	Cost	7.4	7.4	7.4	–	43	9.6	4	18.1	3.1	445	19.4	11	25	7.2	144
ED (m)		422	400	650	72	43	457	100	1400	168.3	445	464	100	500	47.6	144

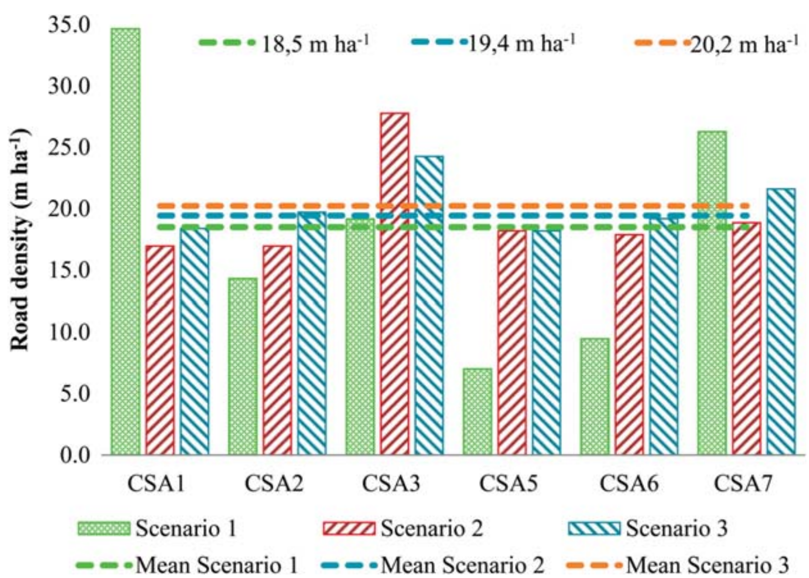
Note: ED – extraction distance; Prod – productivity ($m^3 h^{-1}$); Cost – costs (€ m^{-3}).

stands (Table 15), with consequent savings of two up to three fold. The harvesting productivity was about 40% higher in EA stands than in UA stands. Hence, the costs were about two and a half times lower in the former than in the latter case. This was because in UA stands only motor-manual felling and processing was performed, while in EA forests harvesters and processors had a significant share.

Figure 8 shows that, in general, there is a need for extending the forest road network in most of the CSAs. The mean RD across CSAs in Scenario 1 (18.5 m ha^{-1}) is only about 5% below the mean value in Scenario 2 (19.4 m ha^{-1}) and about 10% below the mean value in Scenario 3 (20.2 m ha^{-1}). Though, the infrastructure situation is different from one CSA to another. For example, CSA1 (Spain) and CSA7 (Bulgaria) reported surplus of infrastructure, when comparing *BAU* with *optimum BAU HS* situation. That is, CSA1 and CSA7 seem to be well equipped with road infrastructure for providing high productivity in timber extraction. However, the productivity of logging operations in these CSAs was rather low (see Table 14) and it seems there are other factors which influence the efficiency of logging operations, such as the quality of the road network (layout and trafficability) and the available harvesting technology. In contrast, CSA2 (France), CSA3 (Austria), CSA5 (Sweden) and CSA6 (Slovakia) revealed road infrastructure gaps. The road networks in these CSAs should be hence extended with new roads in length varying from 6 km to 22 km from case to case, compared to the BAU situation.

Referring to the mean ED, in general, from the economic, environmental and social point of view, good practice examples recommend mean ED below 400 m (Sabo and Porsinsky 2005; Ghaffariyan et al. 2007, 2009b; Eriksson and Lindroos 2014). Indeed, Figure 9 shows that the mean ED in Scenario 1 (501 m) is about 48% higher than in Scenario 2 (338 m) and about 63% higher than in *Scenario 3* (307 m), emphasizing the need for extending and improving the layout of the forest road network. Most of the CSAs require a reduction of the mean ED in order to be more efficient from an economic (i.e. productivity and costs) and environmental point of view (i.e. lower emissions and lower energy requirements). From the social point of view, a lower ED means higher productivity and therefore a lower employment rate, but also improved work safety and ergonomics (Rottensteiner 2014).

Table 16 shows how HS indicators perform in each CSA by scenario (including the mean values across CSAs). By improving only the forest infrastructure to the optimum required for the currently used HS in each CSA (Scenario 2), one can observe (mean value across CSAs) an increase in productivity with 7% and reduction of costs, fuel consumption and CO_{2eq}



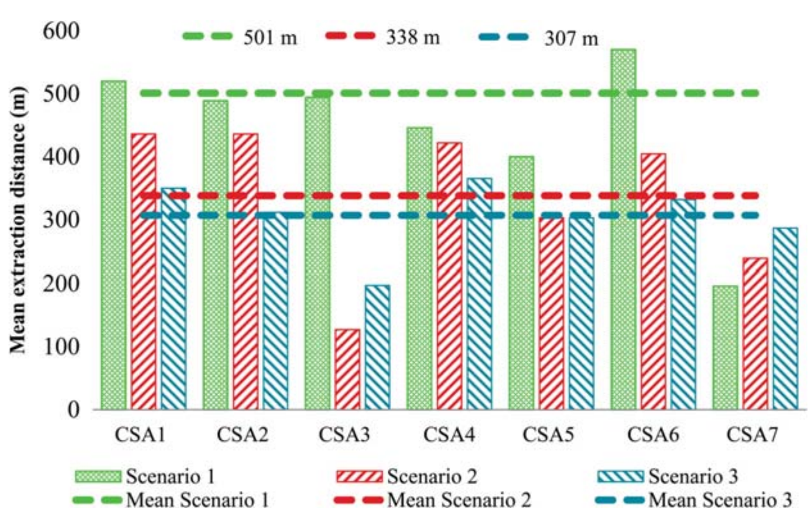
Efficiency gaps of the forest road networks.

Efficiency of logging operations by scenario.

HS indicators	CSA1	CSA2	CSA3	CSA4	CSA5	CSA6	CSA7	Mean CSA
				Scenario 1: BAU				
Productivity (m^3 h^{-1})	9.5	13.0	12.0	13.5	34.3	16.2	4.0	14.6
Cost (€ m^{-3})	33.8	23.0	44.9	29.8	15.8	21.9	15.3	26.4
Consumption (l m^{-3})	2.7	1.8	2.0	1.9	1.7	1.6	3.1	2.1
Accidents (N mill. m^{-3})	87.0	87.0	111.0	83.1	22.0	85.7	126.0	86.0
CO_{2eq} emissions (kg m^{-3})	6.7	4.5	5.3	5.2	5.3	4.2	8.0	5.6
Mean SDI (%)	26.5	26.5	44.0	25.9	17.0	27.4	24.1	27.3
				Scenario 2: Optimum ED_BAU_HS				
Productivity (m^3 h^{-1})	11.6	13.5	14.5	13.7	36.2	14.1	6.6	15.7
Cost (€ m^{-3})	19.7	22.5	38.9	29.5	15.2	24.3	10.4	22.9
Consumption (l m^{-3})	2.0	1.7	1.6	1.9	1.7	1.8	1.9	1.8
Accidents (N mill. m^{-3})	87.0	87.0	111.0	83.1	22.0	85.7	126.0	86.0
CO_{2eq} emissions (kg m^{-3})	5.0	4.3	4.3	5.1	5.1	4.9	4.8	4.8
Mean SDI (%)	26.5	26.5	44.0	25.9	17.0	27.4	24.1	27.3
				Scenario 3: Optimum ED_NEW_HS				
Productivity (m^3 h^{-1})	23.1	23.2	21.2	23.4	36.2	21.6	14.6	23.3
Cost (€ m^{-3})	18.0	19.9	29.2	17.2	15.2	15.9	20.3	19.4
Consumption (l m^{-3})	1.9	1.8	1.6	1.9	1.7	1.9	2.2	1.8
Accidents (N mill. m^{-3})	58.1	61.3	79.0	52.6	22.0	64.2	85.8	60.4
CO_{2eq} emissions (kg m^{-3})	5.5	5.4	4.5	5.5	5.1	5.4	6.1	5.4
Mean SDI (%)	24.4	25.5	34.3	21.5	17.0	25.4	32.1	25.7

Note: SDI – stand damage index.

emissions with 13%, 15% and 15%, respectively, compared to BAU situation (Scenario 1). When both forest infrastructure enhancement and change of current HS with state-of-the-art HS adapted to local terrain conditions in each CSA are realized (Scenario 3 compared with Scenario 1), the possible economic, environmental and social gains could be even higher: increased HS productivity in average by 59%, lower harvesting costs by 26%, lower fuel consumption by 13%, the number of accidents would sink by 30%, while the CO_{2eq} emissions and stand damage index would be with 4% and 6% respectively lower than in BAU situation. Though, the degree of improvement in performance HS indicators varies from one CSA to another by scenario. For example, in BAU scenario, the least performant CSA was CSA7 (Bulgaria), which reported the lowest productivity, the highest fuel consumption rate, the highest number of accidents and the highest CO_{2eq} emissions among CSAs. These are the limitations (disadvantages) of the non-mechanized and obsolete HS used in CSA7. In Scenario 2, CSA7 showed the highest increase in productivity (63%) and the highest reduction of fuel consumption (39%) and CO_{2eq} emissions (40%) amidst CSAs, when compared to Scenario 1. This means that the enhancement of the forest road network in CSA7 plays an important role in overcoming the existing efficiency gaps. In Scenario 3, a manifold increase in productivity was observed in CSA7 and CSA1, and between 73% and 78% higher productivity in CSA2, CSA3 and CSA4 compared to Scenario 1. In addition, cost reduction of up to 47% (CSA1), decrease in number of accidents related to logging operations of up to 37% (CSA4), lower fuel consumption of up to 30% (CSA1 and CSA7), lower CO_{2eq} emissions of up to 23% (CSA7) and a decrease of the mean stand damage index of up to 22% (CSA3) could also be noticed in Scenario 3 compared to Scenario 1. These facts suggest that the well-developed forest infrastructure and the appropriate selection and use of HS according to local specific conditions lead to



Benchmark of EDs across CSAs.

increased efficiency in timber harvesting. The minor changes of HS indicators in CSA5, both in Scenario 2 and Scenario 3 compared to Scenario 1 (6% increase in productivity and the 4% lower costs, fuel consumption and CO_{2eq} emissions) suggest that the BAU HS in CSA5 represent a close to optimal solution (best practice example) and, hence, the performance of these indicators can be used as benchmark values for moderate slope terrain. Indeed, in all scenarios, CSA5 (Sweden) reported the highest productivity, the lowest number of accidents and the lowest stand damage index, thus highlighting the benefits of the fully mechanized HS.

This study showed a wide variability among HS' performance across European mountain forests. There was no common pattern across CSAs for selecting the HS in mountain forests. It seems there was no influence of FM systems on the selection of harvesting and extraction methods, statistics show; neither the slope on the selection of HS.

The quality of the road network (i.e. RD, layout and trafficability) and the long ED were some of the main efficiency gaps identified in this study. Besides their economic (productivity and costs) and environmental (CO_{2eq}emissions, soil erosion and stand damage) impact, poorly developed forest road networks have a negative ergonomic impact on machine operators, due to increased exposure to vibration when driving the forest machinery over long distances (Rottensteiner 2014). Performing forest operations in mountain regions is difficult due to reduced accessibility, steepness and roughness of the terrain. A significant number of accidents in forest operations are related to terrain topography (24% – Potočnik et al. 2009; 22% – Lindroos and Burstrom 2010). From an environmental point of view, timber extraction with skidders should be avoided due to their high damage potential to soil and residual stands, especially when TL method is applied (longer and heavier logs) and the ED is high (Fjeld and Granhus 1998; Košir 2008; Pierzchala et al. 2014; Potočnik et al. 2009; Spinelli et al. 2010). In addition, skidding operations cause a higher incidence of accidents than forwarders (Potcnik et al. 2009; Tsioras et al. 2011). Thus, in terrain with moderate slopes, CTL method should be fostered instead of TL method, and the use of forwarders instead of skidders or tractors, because forwarders provide higher productivity, lower residual damage and safer working conditions. Forwarders, skidders and tractors are not recommended in steep terrain (Eriksson and Lindroos 2014; Borz et al. 2014; Marceta et al. 2014), neither in highly fragmented terrain (e.g. large areas covered by rock outcrops and mixed ground profiles; Sabo and Porsinsky 2005; Mihelič and Krč 2009). Cable yarders are the appropriate extraction mean in such cases in combination with any of the WT, TL or CTL harvesting methods, but the road network should be very well developed, meaning a RD above 25 m ha^{-1} (Kanzian 2003; Ghaffariyan et al. 2010a, 2010b; Talbot et al. 2014). However, this study showed that often inappropriate HS (i.e. animals, skidders and forwarders; CSA1, CSA2, CSA6, CSA7) were used in steep terrain at their technical feasibility limit, with the consequent negative economic, environmental and social impact. For example, although the average slope was above 50% in CSA7, due to the lack of cable yarding technology, non-mechanized extraction was used in 60% of the forest operations and skidding in 35% of the cases. Hence, CSA7 had the lowest productivity, the highest fuel consumption rate, the highest rate of accidents and the highest CO_{2eq} emissions amidst CSAs. However, CSA7 recorded also the lowest harvesting costs (due to the cheap labour costs in Bulgaria) among CSAs, which seems to have made attractive this BAU practice. The minimum cost approach seemed to have been the primary selection criterion of HS in other CSAs. Hence, the following questions arise: *Should the cost minimization approach be the most important criterion of selecting HS? Is this approach sustainable on long term? If not, which actions are required for an appropriate selection and utilization of HS in mountain forests?* Although literature showed that geographic information system and multi-criteria analysis are feasible tools for supporting decision making in timber harvesting (Enache et al. 2013; Kühmaier and Stampfer 2010; Talbot et al. 2014), and as such they could be an appropriate answer to these questions, this study revealed there are still gaps between research and practice in forest engineering, that is in transferring the knowledge into practical know-how.

The productivity and cost of logging operations reported in this study are inside the thresholds presented in literature (see Tables 1 and 2), but the variation between CSAs is very high. The lowest productivity in timber felling and processing was reported in CSA1 (Spain; 1.3 $m^3 h^{-1}$) and CSA7 (Bulgaria; 1.8 $m^3 h^{-1}$), while the highest was in CSA5 (Sweden; 16.6 $m^3 h^{-1}$). If the reason for the very high productivity in Sweden is the use of harvesters, the low productivity in Spain and Bulgaria can be explained by the use of chainsaw, the lack of proper training of forest workers and the small dimension trees, especially in coppice FM (CSA1). The efficiency of timber extraction is influenced by the ED. In general, a shorter ED leads to higher productivity and lower extraction costs, but the efficiency of logging operations depends also on other factors like terrain condition, method of harvesting, degree of mechanization and type and capacity of the machinery used. For shorter distances, small amount of timber and low tree volume, animal logging and manual extraction may be used, although the productivity is low (Borz and Ciobanu 2013; Gumus and Acar 2010). Though, this study revealed that from economic, environmental and social point of view, fully mechanized systems (i.e. CSA5) proved to be much more efficient than non-mechanized or partly mechanized HS (e.g. CSA2, CSA3, CSA4 and CSA7). The lowest extraction costs were reported in CSA5 (Sweden) that is 6.1 € m^{-3} for timber extraction with forwarders, while the highest extraction costs were reported in CSA3 (Austria), 24.9 € m^{-3} for timber extraction with cable yarders. The higher costs in Austria were a consequence of the low productivity (8.0 $m^3 h^{-1}$) and high system costs of cable yarders, usually between 185.0 and 205.0 € h^{-1} (Ghaffariyan et al. 2009a, 2010a). The high costs of cable yarding can be seen as an environmental cost, since cable yarders have a lower environmental footprint than other extraction technologies. In contrast, the higher environmental impact of skidders is compensated by lower extraction costs (9.1 € m^{-3}).

When comparing the BAU harvesting practices with a close to optimal desired state (Scenario 3), this study showed that, apart from CSA5 (Sweden), all CSAs suffer from efficiency gaps in productivity, costs, number of accidents in logging operations, CO_2 emissions and residual stand damage. Speculating on the possible causes of these gaps, the reasons vary amidst CSAs, but some of the most important ones are: the quality of the forest road network (density, layout and trafficability); the low mechanization degree; the inappropriate selection of HS according to specific local conditions; the level of know-how and training of forest workers; the availability and the affordability of state-of-the-art HS; and the CSA's country specific characteristics (i.e. policies and financial support). Some of the possible measures that could help overcoming these gaps might be: capacity building and knowledge transfer (from research to practice) about selection of the appropriate HS in mountain areas (e.g. multiple criteria decision making); better planning and scheduling of logging operations; fostering the utilization of CTL method; increasing the mechanization degree and shifting from outdated or inappropriate HS to state-of-the-art HS (harvesters, forwarders and cable yarders) adapted to local conditions; training forest workers and know-how transfer for operating state-of-the-art HS; extending the forest road networks and improving their layout and trafficability; provision of financial support schemes for investing in state-of-the-art HS. These actions should represent a priority of the national forest policies across EU since they would not only improve the economic and environmental efficiency of logging operations, but they would also provide more attractive and safer working conditions for the forest workers.

We would also like to thank the two anonymous peer-reviewers for their valuable comments and suggestions.

No potential conflict of interest was reported by the authors

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 289437 – ARANGE Project.

Albizu-Urionabarrenetxea PM, Tolosana-Esteban E, Roman-Jordan E. 2013. Safety and health in forest harvesting operations. Diagnosis and preventive actions. A review. Forest Syst. 22:392–400. doi:10.5424/fs/2013223-02714

Ambrušová L, Halaj D, Ilavsky J, Marttila J. 2013. Atlas of the forest sector in Slovakia. Working papers of the Finnish Forest Research Institute 257, Finnish Forest Research Institute, Vanta (Finland).

Axelsson R, Angelstam P. 2011. Uneven-aged forest management in boreal Sweden: local forestry stakeholders' perceptions of different sustainability dimensions. *Forestry*. 84:567–579. doi:10.1093/forestry/cpr034

Berg S, Karjalainen T. 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. *Forestry*. 76:271–284. doi:10.1093/forestry/76.3.271

Berg S, Fischbach J, Brüchert F, Poissonnet M, Pizzirani S, Varet A, Sauter UH. 2012. Towards assessing the sustainability of European logging operations. *Eur J For Res*. 131:81–94. doi:10.1007/s10342-011-0561-x

Berg S, Schweier J, Brüchert F, Lindner M, Vlainger E. 2014. Economic, environmental and social impact of alternative forest management in Baden-Württemberg (Germany) and Västerbotten (Sweden). *Scand J For Res*. 29:485–498. doi:10.1080/02827581.2014.927913

Brang P, Spathelf P, Larsen JB, Bauhus J, Boncina A, Chauvin C, Drössler L, Garcia-Güemes C, Heiri C, Kerr G et al. 2014. Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry*. 0:1–12.

Borz SA, Dinulica F, Birda M, Ignea G, Ciobanu DV, Popa B. 2013. Time consumption and productivity of skidding silver fir (*Abies alba* Mill.) round wood in reduced accessibility conditions: a case study in windthrow salvage logging from Romanian Carpathians. *Ann For Res*. 56:363–375.

Borz SA, Ciobanu DV. 2013. Efficiency of motor-manual felling and horse logging in small-scale firewood production. *Afr J Agr Res*. 8:3126–3135.

Borz SA, Ignea G, Popa B. 2014. Assessing timber skidding efficiency in a group shelterwood system applied to a fir-beech stand. *Afr J Agr Res*. 9:160–167. doi:10.5897/AJAR2013.7537

Contreras M, Chung W. 2007. A computer approach to finding an optimal log landing location and analysing influencing factors for ground-based timber harvesting. *Can J For Res*. 37:276–292. doi:10.1139/x06-219

Diaci J, Kerr G, O'Hara K. 2011. Twenty-first century forestry: integrating ecologically based, uneven-aged silviculture with increased demands on forests. *Forestry*. 84:463–465. doi:10.1093/forestry/cpr053

Enache A, Kühmaier M, Stampfer K, Ciobanu VD. 2013. An integrative decision support tool for assessing forest road options in a mountainous region in Romania. *Croatian J For Eng*. 34:43–60.

Enache A, Stampfer K. 2015. Machine utilization rates, energy requirements and greenhouse gas emissions of forest road construction and maintenance in Romanian mountain forests. *J Green Eng*. 4:325–350. doi:10.13052/jge1904-4720.445

Eriksson M, Lindroos O. 2014. Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *Int J For Eng*. 25:179–200.

European Commission. 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new EU Forest Strategy: for forests and the forest-based sector – COM (2013) 659 final

Eurostat. 2015. Statistics explained. Forestry statistics [Internet]. [cited 2015 Mar 23] Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Forestry_statistics.

Fjeld D, Granhus A. 1998. Injuries after selection harvesting in multi-stored spruce stands – the influence of operating systems and harvest intensity. *J For Eng*. 9:33–40.

FOREST EUROPE, UNECE, FAO. 2011. State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe, Ministerial Conference on the Protection of Forests in Europe – Forest Europe Liaison Unit Oslo, Äs (Norway).

Ghaffariyan MR, Stampfer K, Sessions J. 2007. Forwarding productivity in Southern Austria. *Croatian J For Eng*. 28:169–175.

Ghaffariyan MR, Sobhani H. 2008. Optimum road spacing of ground based skidding operations in Nowshahr, Iran. *Caspian J Environ Sci*. 6:105–112.

Ghaffariyan MR, Stampfer K, Sessions J. 2009a. Production equations for tower yarders in Austria. *Int J For Eng*. 20:17–21.

Ghaffariyan MR, Stampfer K, Sessions J. 2009b. Comparison of three methods to determine optimal road spacing for forwarder-type logging operations. *J For Sci*. 55:423–431.

Ghaffariyan MR, Stampfer K, Sessions J. 2010a. Optimal road spacing of cable yarding using a tower yarder in southern Austria. *Eur J For Res*. 129:409–416. doi:10.1007/s10342-009-0346-7

Ghaffariyan MR, Stampfer K, Sessions J, Durston T, Kühmaier M, Kanzian C. 2010b. Road network optimization using heuristic and linear programming. *J For Sci*. 56:137–145.

Gordon M, Lockwood M, Vanclay F, Hanson D, Schirmer J. 2012. Divergent stakeholder views of corporate social responsibility in the Australian forest plantation sector. *J Environ Manage*. 113:390–398. doi:10.1016/j.jenvman.2012.09.016

Gumus S, Acar HH. 2010. Evaluation of consecutive skylines yarding and gravity skidding systems in primary forest transportation on steep terrain. *J Environ Biol*. 31:213–218.

Heinimann HR. 1998. A computer model to differentiate skidder and cable-yarder based road network concepts on steep slopes. *J For Res*. 3:1–9. doi:10.1007/BF02760286

Heinimann HR. 2012. Life cycle assessment (LCA) in Forestry – state and perspectives. *Croatian J For Eng*. 33:357–372.

Holzleitner F, Stampfer K, Visser R. 2011. Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croatian J For Eng*. 32:501–508.

Jänich K. 2011. Unfallbericht 2011 [Accident report 2011]. Niedersächsisches Forstliches Bildungszentrum.

Jirousek R, Klvac R, Skoupy A. 2007. Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. *J For Sci.* 53:476–482.

Kanzian C. 2003. Modelle zur Abschätzung der Installationszeit von Seilgeräten [Models for estimating set up time of cable yarders] [Master thesis]. Vienna (Austria): University of Natural Resources and Life Sciences.

Kastner M. 2014. Identifikation von Nachhaltigkeitslücken bei der Waldbewirtschaftung in einem rumänischen kommunen Forstbetrieb [Identification of efficiency gaps in forest management for a Romanian municipial forest enterprise] [Master thesis]. Vienna (Austria): University of Natural Resources and Life Sciences.

Klopcic M, Pardos M, Leitner T, Stampfer K, Lexer MJ. 2013. ARANGE Deliverable D1.3 – Annex 1: Forest management practices in case study areas: the operational description of a questionnaire, ARANGE Project.

Klvač R, Fischer R, Skoupy A. 2012. Energy use of and emissions from the operation phase of a medium distance cableway system. *Croatian J For Eng*. 33:79–88.

Košir B. 2008. Damage to young forest due to harvesting in shelterwood systems. *Croatian J For Eng*. 29:141–153.

Kühmaier M, Stampfer K. 2010. Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. *Croatian J For Eng*. 31:75–88.

Kühmaier M, Stampfer K. 2012. Development of a multi-criteria decision support tool for energy wood supply management. *Croatian J For Eng*. 33:181–198.

Lehman A, O'Rourke N, Hatcher L, Stepanski EJ. 2005. *JMP for basic univariate and multivariate statistics: a step-by-step guide*. Cary, NC: SAS Institute.

Leitner T, Klopcic M, Pardos M, Cordonnier T, Maroschek M, Wilhelmsson E, Hlasny T, Zlatanov T, Lexer MJ. 2013. ARANGE Deliverable D1.3 – Annex 3: Harvesting technologies in representative stand types per case study areas, ARANGE Project.

Limbeck-Lilienau B. 2004. Residual stand damage caused by mechanised harvesting systems. In: Proceedings of the Austro2003 meeting: High Tech Forest Operations for Mountainous Terrain, Limbeck-Lilienau, Steinmüller and Stampfer (editors); 2003 October 5–9; Schlaegl (Austria).

Laiho O, Lähde E, Pukkala T. 2011. Uneven- vs even-aged management in Finnish boreal forests. *Forestry*. 84:547–556. doi:10.1093/forestry/cpr032

Laina R, Tolosana E, Ambrosio Y. 2013. Productivity and cost of biomass harvesting for energy production in coppice natural stands of *Quercus pyrenaica Willd*. in central Spain. *Biomass Bioenergy*. 56:221–229. doi:10.1016/j.biombioe.2013.04.016

Laitila J, Asikainen A, Nuutinen Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. *Int J For Eng*. 18:29–39.

Lebel L, Nadeau FR, Valeria O. 2003. Optimizing the combined harvesting and road construction costs for a dispersed harvesting regime. In: Proceedings of the Council on Forest Engineering (COFE): Forest operations among competing forest uses; 2003 September 7–10; Bar Harbor – Maine (USA).

Levers C, Verkerk PJ, Müller D, Verburg PH, Butsic V, Leitao PJ, Lindner M, Kuemmerle T. 2014. Drivers of forest harvesting intensity patterns in Europe. *For Ecol Manage*. 315:160–172. doi:10.1016/j.foreco.2013.12.030

Lexer MJ. 2013. Catalogue of harmonized environmental variables. Deliverable D1.2 – ARANGE Project.

Lindroos O, Burstrom L. 2010. Accident rates and types among self-employed private forest workers. *Accid Anal Prevent*. 42:1729–1735. doi:10.1016/j.aap.2010.04.013

Magagnotti N, Spinelli R. 2011. Integrating animal and mechanical operations in protected areas. *Croatian J For Eng*. 32:489–499.

Marceta D, Petkovic V, Kosir B. 2014. Comparison of two skidding methods in beech forests in mountainous conditions. *New Forestry Mechanization*. 35:51–62.

Mathews JD. 1999. *Silvicultural systems*. New York: Oxford University Press.

Matilainen AM. 2013. Forest companies, corporate social responsibility, and company stakeholders in the Russian forest sector. *For Policy Econ*. 31:44–49. doi:10.1016/j.forpol.2011.12.006

Mihelič M, Krč J. 2009. Analysis of inclusion of wood forwarding into a skidding model. *Croatian J For Eng*. 30:113–125.

Nordregio – Nordic Centre for Spatial Development. 2004. Mountain areas in Europe: analysis of mountain areas in EU member states, acceding and other European countries. European Commission contract No 2002.CE.16.0.AT.136. Nordregio, Stockholm (Sweden).

Nurminen T, Korpunen H, Uusitalo J. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fenn*. 40:335–363. doi:10.14214/sf.346

Nyland RD. 2002. *Silviculture: Concepts and Applications – 2nd Edition*. New York: The McGraw-Hill Companies.

Olsson L. 2005. Road investment in Northern Sweden. *For Policy Econ*. 7:615–623. doi:10.1016/j.forpol.2003.11.002

Pellegrini M, Grigolato S, Cavalli S. 2013. Spatial multi-criteria decision process to define maintenance priorities of forest road network: an application in the Italian Alpine region. *Croatian J For Eng*. 34:31–42.

Pentek T, Pičman D, Potočnik I, Dvorsčak P, Nevečerel H. 2005. Analysis of an existing forest road network. *Croatian J For Eng*. 26:39–50.

Pentek T, Pičman D, Nevečerel H, Lepoglavec K, Papa I, Potočnik I. 2011. Primary forest opening of different relief areas in the Republic of Croatia. *Croatian J For Eng*. 32:401–416.

Pepke E. 2007. Today's and tomorrow's timber resources: can we sustainably meet rising demand? In: Wood Futures Conference, 2007 November 8, London (UK). [Internet]. [cited 2014 May 15] Available from: https://www.unece.org/fileadmin/DAM/timber/mis/presentations/PepkeForResMktFuturesPublic081107.pdf.

Petty A, Kärhä K. 2014. Productivity and cost evaluations of energy-wood and pulpwood harvesting systems in first thinnings. *Int J For Eng*. 25:37–50.

Peters PA. 1978. Spacing of roads and landings to minimize timber harvest costs. *For Sci*. 24:209–217.

Pierzchala M, Talbot B, Astrup R. 2014. Estimating soil displacement from timber extraction trails in steep terrain: application of an unmanned aircraft for 3D modelling. *Forests*. 5:1212–1223. doi:10.3390/f5061212

Potočnik I, Pentek T, Poje A. 2009. Severity analysis of accidents in forestry operations. *Croatian J For Eng*. 30:171–184.

Price MF, Gratzer G, Duguma LA, Kohler T, Maselli D, Romeo R. ed. 2011. Mountain Forests in a Changing World - Realizing Values, addressing challenges. Rome (Italy): FAO/MPS and SDC.

Raab S, Feller S, Uhl E, Schäfer A, Ohrner G. 2002. Aktuelle Holzernteverfahren am Hang [State-of-the-art timber harvesting systems in steep terrain]. Freising (Germany): Bayerische Landesanstalt für Wald und Forstwirtschaft.

Robek R, Bogataj N, Klun J, Krajnc N, Mavsar R, Ogris N, Piskur M, Medved M. 2005. Forest operation improvements in farm forestry in Slovenia – encouragement of advanced operation methods among forest owners in local community. FAO Forest Harvesting Case-Study.

Rottensteiner C. 2014. Vibration analysis of forest operations and road construction [Dissertation]. Vienna (Austria): University of Natural Resources and Life Sciences.

Sabo A, Porsinsky T. 2005. Skidding of fir roundwood by Timberjack 240C from selective forests of Gorski Kotar. *Croatian J For Eng*. 26:13–27.

Sampson RN, Bystriakova N, Brown S, Gonzalez P, Irland LC, Kauppi P, Sedjo R, Thompson ID, Barber CV, Offrel R. 2005. Timber, fuel, and fiber. In: Hassan R, Scholes R, Ash N, editor. Ecosystems and human well-being: current state and trends – volume 1 – findings of the condition and trends working group (Millenium Ecosystem Assessment), Island Press: p. 243–269, Washington (USA).

Sessions J, Boston K. 2006. Optimization of road spacing for log length shovel logging on gentle terrain. *Int J For Eng*. 17:67–75.

Siren M, Hyvönen J, Surakka H. 2015. Tree damage in mechanized uneven-aged selection cuttings. *Croatian J For Eng*. 36:33–42.

Slamka M, Radocha M. 2010. Results of harvesters and forwarders operations in Slovakian forests. *Lesnicky časopis – For J*. 56:1–15.

Slugen J, Peniasko P, Messingerova V, Jankovsky M. 2014. Productivity of a John Deere harvester unit in deciduous stands. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*. 62:231–238. doi:10.11118/actaun201462010231

Soom E. 1950. The cost of skidding and the spacing of forest roads. *Schweiz Z Forstwes*. 101:546–560.

Spinelli R, Magagnotti N, Nati C. 2010. Benchmarking the impact of traditional small-scale logging systems used in Mediterranean forestry. *For Ecol Manage*. 260:1997–2001. doi:10.1016/j.foreco.2010.08.048

Spinelli R, Magagnotti N, Relano RL. 2012. An alternative skidding technology to the current use of crawler tractors in Alpine logging operations. *J Clean Prod*. 31:73–79. doi:10.1016/j.jclepro.2012.02.033

Spinelli R, Magagnotti N, Facchinetti D. 2013. Logging companies in the European mountains: an example from Italian Alps. *Int J For Eng*. 24:109–120.

Stampfer K, Limbeck-Lilienau B, Kanzian C, Viertler K. 2003. Baumverfahren im Seilgelände – Wanderfalke mit Prozessor Woody 50, Syncrofalke mit Prozessor Wolf 50B [Whole-tree method in steep terrain – Wanderfalke with processor Woody 50, Syncrofalke with processor Wolf 50B]. Vienna (Austria): Forst Holz Papier.

Stanescu RC. 2012. Research concerning production technologies and properties of biofuels for vehicles [Dissertation]. Brasov (Romania): Transilvania University of Brasov.

Statistics Norway. 2009. Natural Resources and the Environment 2008 – Norway. Statistical Analyses Statistics Norway, Oslo-Kongsvinger (Norway).

Steirer F, Hetsch S, Prins K, Mantau U. 2007. Wood resources availability and demands – implications of renewable energy policies – A first glance at 2005, 2010 and 2020 European countries (a study elaborated with joint efforts of UNECE – FAO – University of Hamburg – European Commission), [Internet]. [cited 2014 Aug 19] Available from: http://www.unece.org/fileadmin/DAM/timber/docs/tc-sessions/tc-65/policyforum/Wood_availability_and_demand.pdf.

Svenson G, Fjeld D. 2014. The impact of road geometry and surface roughness on fuel consumption for Swedish logging trucks. In: Proceedings of the Transport Research Arena 2014, 2014 April 14–17, Paris (France).

Talbot B, Tarp P, Nitteberg M. 2014. Selecting an appropriate excavator-based yarder concept for Norwegian conditions through analytic hierarchy process. *Int J For Eng*. 25:113–123.

Thompson MA. 1992. Considering overhead costs in road and landing spacing models. *J For Eng*. 3:13–19.

Thurner C, Klopf M, Hasenauer H. 2011. Forests in transition: a harvesting model for uneven-aged mixed species forests in Austria. *Forestry*. 84:517–526. doi:10.1093/forestry/cpr021

Tolosana E, Laina R, Ambrosio Y, Martin M. 2014. Residual biomass recovery from fully-mechanized delayed thinnings on Spanish Pinus spp. plantations. *Biomass Bioenergy*. 71:98–105. doi:10.1016/j.biombioe.2014.10.022

Tsioras P, Rottensteiner C, Stampfer K. 2011. Analysis of accidents during cable yarding operations in Austria 1998–2008. *Croatian J For Eng*. 32:549–560.

Tsioras P, Rottensteiner C, Stampfer K. 2014. Wood harvesting accidents in the Austrian State Forest Enterprise 2000–2009. *Saf Sci*. 62:400–408. doi:10.1016/j.ssci.2013.09.016

Vusić D, Susnjar M, Marchi E, Spina R, Zecic Z, Picchio R. 2013. Skidding operations in thinning and shelterwood cut of mixed stands – work productivity, energy inputs and emission. *Ecol Eng*. 61:216–223. doi:10.1016/j.ecoleng.2013.09.052

Yonov N, Velichkov V. 2004. Country report – Bulgaria. In: Proceedings of the FAO/Czech Republic Forestry Policy Workshop “Trends in Forest Use and Conservation – Policy Options for Action”; 2004 March 21–26; Hrubá Skála (Czech Republic).

Zečič Ž, Marenč J. 2005. Mathematical models for optimization of group work in harvesting operation. *Croatian J For Eng*. 26:29–37.

Whittaker C, Mortimer N, Murphy R, Matthews R. 2011. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass Bioenergy*. 35:4581–4594. doi:10.1016/j.biombioe.2011.07.001

Wirth J, Wolff D. 2008. Vergleich von Pferde- und Seilschleppereinsatz beim Vorliefern von Vollbäumen [Comparison of pre-extraction of whole-trees by horses and skidders]. *AFZ-DerWald*. 18:968–971.

Publication II

Accepted 10th April 2013 - published online and print

An Integrative Decision Support Tool for Assessing Forest Road Options in a Mountainous Region in Romania

Adrian Enache, Martin Kühmaier, Karl Stampfer, Valentina Doina Ciobanu

Abstract – Nacrtak

Sound development of forest infrastructure represents the backbone for sustainable forest management. However, planning forest roads, which nowadays must fulfill multiple conflicting objectives, is not an easy task. A GIS based model was developed for supporting decision making in forest road engineering. The tool allowed assessment of forest infrastructure scenarios based on multiple criteria analyses, considering stakeholders' interests, economic, ecological and social aspects. First, the decision problem was clearly structured and then criteria and sub-criteria were weighted. Then, forest road scenarios were defined and quantitative and qualitative assessments regarding infrastructure and harvesting systems were performed. In the end, utility analysis for each scenario was conducted, the forest road variant with the highest utility score being selected as the most suitable option for implementation. The model was tested and validated in a mountain forest area from Brasov County, Romania. Reduction of mean skidding distance from 864 m to 255–268 m was reported, leading to an increase in productivity of timber extraction from 7.5 m^3/h to 11.7 m^3/h and to an increased contribution margin from 21.2 €/m^3 to 25.1 €/m^3. Enhancement of forest infrastructure reduced CO_2 emissions re timber harvesting and transport from 8.52 kg/m^3 to 7.3 kg/m^3. This study showed how multiple attribute utility theory could be used in assessing different forest road options based on a participatory approach.

Keywords: forest roads, multiple criteria decision making, utility analysis, decision support tool, participatory approach

1. Introduction – *Uvod*

Enhancing forest infrastructure has always been a topic of interest among specialists in their quest to provide sound approaches for improving forest accessibility in the context of sustainable forest management (SFM). Several studies have been published regarding automation of road locating (Akay et al. 2005; Aruga 2005; Rogers 2005; Stückelberger et al. 2007) or regarding the impact of forest roads on the environment (Coulter 2004; Akay 2004). However, most of these studies are based on assessments of only one objective function. Recently, Kühmaier et al. (2010) developed a multi-attribute spatial decision support tool for selecting the best suited harvesting systems, taking into account ecological, economic and social aspects. In addition, recent studies have shown that forest roads fulfill multiple functions; they are of strategic importance in forest operations, they allow access to remote areas, in cases of natural hazards, for tourism and recreational activities (Popovici et al. 2003; Stampfer 2007; Kühmaier et al. 2010). Sustainable development of the forest infrastructure requires harmonization of road planning, designing, construction and maintenance with operational harvesting plans. Thus, planning of forest road routes and skid trails should be approached simultaneously (Pentek et al. 2007). Consideration of environmental and social aspects from the early stages of planning have also been acknowledged (Popovici et al. 2003; Gumus et al. 2008; Ciobanu et al. 2011), underlining the necessity of performing impact assessments when developing forest infrastructure. Dürrstein (1998) proposed an extensive approach system of cost-efficiency analysis of forest road options, underlining the importance of participatory process in decision making, while Heinimann (1998) stressed the planning phase should consider assessment of the technical feasibility of alternatives, environmental impact and public involvement in decision making. Though, dealing with so many variables and constraints is not an easy task for road planners and decision makers. In Romania, Zarojanu (2006, 2007) described a multi-criteria analysis model for optimizing the selection of most suitable forest road option, focusing on the technical aspects of the roads and only marginally addressing the environmental and social aspects. However, these aspects are particularly important for the development of the Romanian forestry sector. The former national strategy (Ministry of Environment and Forests – MEF 2011a) envisaged the expansion of forest infrastructure in conjunction with GIS, timber harvesting technologies and environmental constraints. Whilst several strategic actions were established in this respect (i.e. developing secondary forest infrastructure; fostering the utilization of environmentally friendly harvesting technologies), none of these have been implemented so far on large scale in Romania. Moreover, although the road density in Romanian forests is very low (6.5 m/ha, Enescu 2011), the rate of forest road network expansion is also very low (Bereziuc et al. 2003; MEF 2011b). Skidding is the main method for timber extraction, using winch tractors, skidders, gravitational hauling, ox or horse harnesses, while very few forwarders or cable yarders are used. The mean skidding distance at the national level is 1.8 km (Popovici et al. 2003), consequently with a very low productivity in timber extraction. A peculiarity of the Romanian forest sector is the timber sales procedure: on stump or at the road side. In the first case, timber is sold on stump at auctions. Contractors

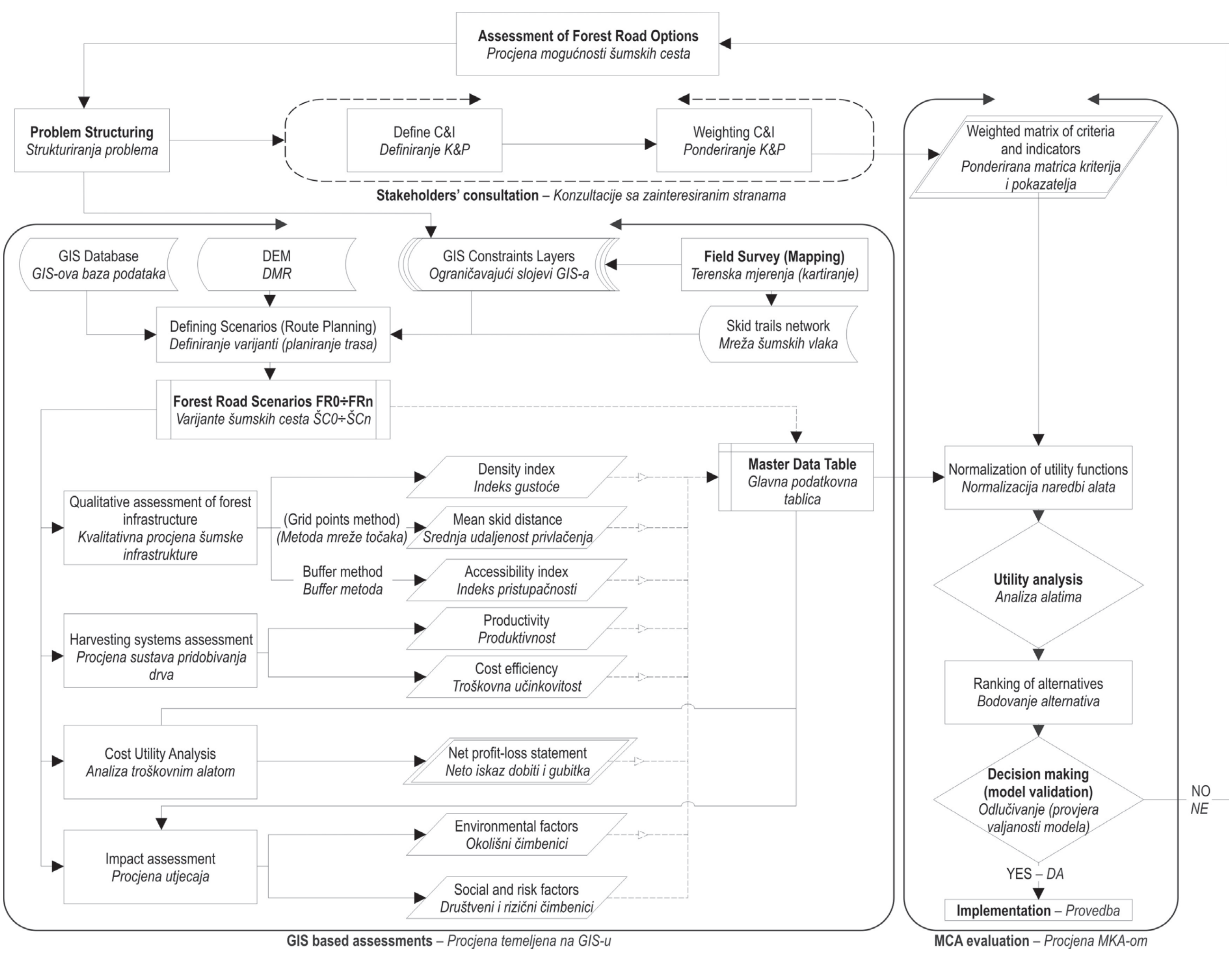


Fig. 1 Schematic representation of processes in the decision making tool
Slika 1. *Shematski prikaz procesa u alatu za odlučivanje*

then harvest and sell the timber either at the road side or directly to the mill. This behavior triggered empiric development of skid trails, leading to increased residual stand damage and soil erosion. In the second case, harvesting operations are externalized by forest owners, which then sell the timber at the road side.

A well-developed forest infrastructure is a prerequisite for sustainable development of the forest sector. Thus, the traditional Romanian behavior of building valley forest roads should be changed toward building slope roads that fulfill multiple objectives (Enache et al. 2012). In Romania for decades significant emphasis

Table 1 Criteria and sub-criteria used to measure the performance of forest road alternatives

Tablica 1. *Kriteriji i potkriteriji za određivanje performansi varijanata šumskih cesta*

Criterion *Kriterij*	Sub-criterion *Potkriterij*	Efficiency Scale (Indicator) *Ljestvica učinkovitosti (pokazatelj)*	Unit *Jedinica*	Objective function *Objektivno djelovanje*
A. Management *A. Upravljanje*	A1. Independence from neighors *A1. Neovisnost o susjedstvu*	1= only own property, 0= over neighbors property *1 = samo preko vlastite imovine, 0 = preko susjedne imovine*	–	
	A2. Accessibility for execution of forest operations *A2. Pristupačnost za izvođenje šumskih radova*	% of areas in the 300 m corridor from forest roads *Postotak područja do 300 m udaljena od šumskih cesta*	%	max
	A3. Accessibility for game management *A3. Pristupačnost za lovno gospodarenje*	Maximum distance from the road to the furthest point in the project area *Najveća udaljenost od ceste do najudaljenije točke u projektnom području*	m	min
	A4. Loss of productive land (road bed clearance) *A4. Gubitak produktivne površine (oduzeto planumom ceste)*	Road length X Opening width *Duljina ceste X Oduzeta širina*	ha	min
B. Costs *B. Troškovi*	B1. Road construction costs *B1. Troškovi izgradnje cesta*	Annuity of investment effort *Renta od uloženoga napora*	€/year €/godini	min
	B2. Road maintenance costs *B2. Troškovi održavanja cesta*	Total yearly maintenance costs *Ukupni godišnji troškovi održavanja*	€/year €/godini	min
	B3. Harvesting costs *B3. Troškovi pridobivanja drva*	Total yearly harvesting costs *Ukupni godišnji troškovi pridobivanja drva*	€/year €/godini	min
C. Environment protection *C. Zaštita okoliša*	C1. Protection of ecological valuable areas *C1. Zaštita ekološki vrijednih područja*	Total cumulated distance to ecological valuable areas *Ukupno zbrojena udaljenost do ekološko vrijednih područja*	m	max
	C2. Air pollution *C2. Onečišćenje zraka*	CO_2 Emissions from harvesting machineries and timber trucks *Emisija CO_2 od strojeva za pridobivanje drva i kamiona*	kg/m^3	min
	C3. Visual disturbance of landscape *C3. Vizualno narušavanje krajolika*	Number of curves, serpentines, intersections *Broj krivina, serpentina, raskrižja*	no.	min
D. Social factors and risks *D. Socijalni čimbenici i rizici*	D1. Accidents in forest operations *D1. Nesreće na šumskim poslovima*	Time needed for first aid teams to arrive at accident location *Vrijeme potrebno za dolazak hitne pomoći na mjesto nesreće*	min	min
	D2. Risk of soil erosion and landslides *D2. Rizik od erozije tla i klizišta*	Risk factor calculated based on models of soil erosions *Čimbenici rizika izračunati na temelju modela erozije tla*	–	min
	D3. Accessibility for touristic/local/cultural purpose *D3. Pristupačnost za turističke, lokalne, kulturne interese*	Cumulated distance to the points of interest *Zbrojena udaljenost do točaka interesa*	m	min
	D4. Accessibility in case of forest fires *D4. Pristupačnost u slučaju požara*	Proportion of areas in the 200 m corridor from forest roads *Postotak područja do 200 m udaljena od šumskih cesta*	%	max
	D5. Accessibility in case of wind- throws *D5. Pristupačnost u slučaju vjetroizvala i snjegoloma*	Proportion of areas in the 300 m corridor from forest roads *Postotak područja do 300 m udaljena od šumskih cesta*	%	max

has been put merely on technical design of forest roads and only recently (Zarojanu 2007; Ciobanu et al. 2011; MEF 2012) environmental aspects have started to be considered in forest road planning.

In this particular context, the aim of this study was to develop an integrative decision support tool for evaluating forest road options based on economic, environmental and social constraints, considering multiple stakeholders' interests. The main focus was to guide decision makers in selecting the most suitable forest road option using GIS and multiple criteria analyses. The conceptual model was developed and applied in a mountain forest area in Romania and could be used in other areas with similar local conditions.

2. Material and Methods – *Materijal i metode*

Forest road engineering involves complex decision problems and conflicting objectives that need to be handled simultaneously. Technical feasibility, environmental soundness, social acceptance and economic affordability are the four main pillars on which forest infrastructure must be built (Stampfer 2007). The conceptual model, which includes all these aspects in the decision process and shows the flow of the main processes, is shown in Fig. 1. Based on this model, workflows can be performed individually or simultaneously, depending on the level of automation and on the available data sets. A master table containing sections with input and output data for each work flow process of the decision tool was created. Data from GIS databases, DEMs and forest management plan, as well as results of GIS analyses, cost appraisal, environmental impact evaluation and intermediate results of workflow processes were used as input in the overall utility analysis of the forest road alternatives.

2.1 Structuring a complex decision problem *Strukturiranje problema kompleksnoga odlučivanja*

The complex management problem of enhancing forest infrastructure requires good structuring, with clearly defined goals and objectives. Thus, based on multiple criteria decision analysis tools (Coulter 2004; Lexer et al. 2005; Green et al. 2010), the decision problem has been defined as follows: »which is the most suitable variant of the forest road that should be implemented considering multiple stakeholders' interests?«. The problem has then been hierarchically decomposed into four main objectives (criteria) and fifteen subobjectives (sub-criteria) used in the evaluation of different forest road options (Table 1).

2.2 Multiple criteria utility model for alternatives evaluation – *Multikriterijski model korisnosti za vrednovanje varijanata*

For the evaluation of forest road alternatives based on stakeholders' preferences, multiple attribute utility theory (MAUT) has been used. One of the most applied MAUT formulas is the linear additive utility function (Kangas et al. 2008, Greene et al. 2010).

$$U_{\mathrm{i}} = \sum_{\mathrm{j}=1}^{\mathrm{m}} a_{\mathrm{j}} \cdot c_{\mathrm{ji}}$$

U_i – the overall utility of alternative i,
c_{ji} – performance of alternative i with respect to criterion j (normalized value),
a_j – importance weight (preference) of criterion j.

The sum of preference weights is required to be 1. As sub-criteria are characterized by different efficiency scales with different measurement units, as a first step, all cardinal values of the sub-criteria were normalized to a common comparable scale. In order to do so, the score range procedure was applied, resulting in local values of each indicator, which follow an interval utility scale (Kangas et al. 2008).

$$v_{\mathrm{i}} = \frac{c_{\mathrm{i}} - \min(c)}{\max(c) - \min(c)}$$

where:
v_i – normalized value of criterion i,
c_i – cardinal value of alternative i in the natural scale.

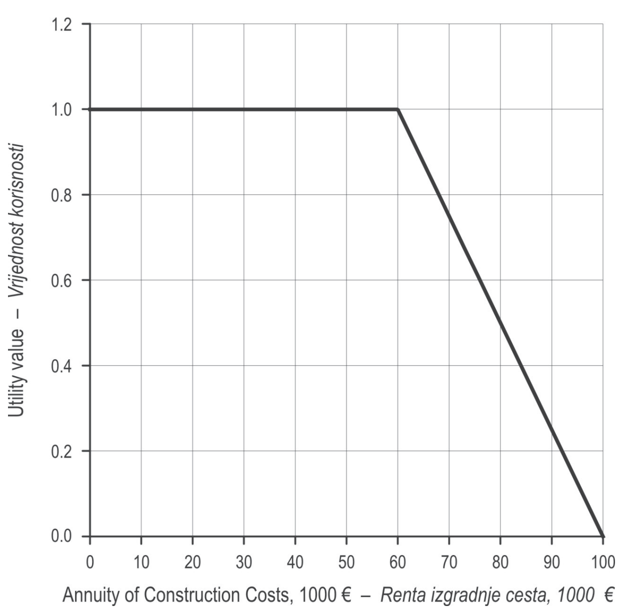


Fig. 2 Utility function for road construction costs sub-criterion
Slika 2. *Funkcija korisnosti za potkriterij trošak izgradnje cesta*

The best alternative was assumed to have the value 1, while the worst had the value 0. It was possible to define thresholds above or below which the function had a constant value. This was particularly important when referring to sub-criteria with a very big variance between alternative values. For example, in case of road construction costs sub-criterion, the linear utility function had the value 1 below 60 000 € and the value 0 above 100 000 € (Fig. 2).

Another possibility would be to use the ratio scale approach, where the criterion values for each alternative are divided with the maximum value among alternatives. Again, the best alternative has the value 1, while the worst has the value 0 (Kangas et al. 2008).

$$v_i = \frac{c_i}{\max(c)}$$

Normalized values of each sub-criterion, for each alternative, were then multiplied with their respective importance weights and then summed up, resulting in the final score of an alternative (Greene et al. 2010).

The importance weights for each criterion have been derived based on preferences of different groups of stakeholders (e.g. forest owner, forest manager, environmental protection agency, forest contractor, other authorities) from the Romanian forest sector, through a nationwide survey. Stakeholders were requested to fill their field of expertise and to rate their preferences

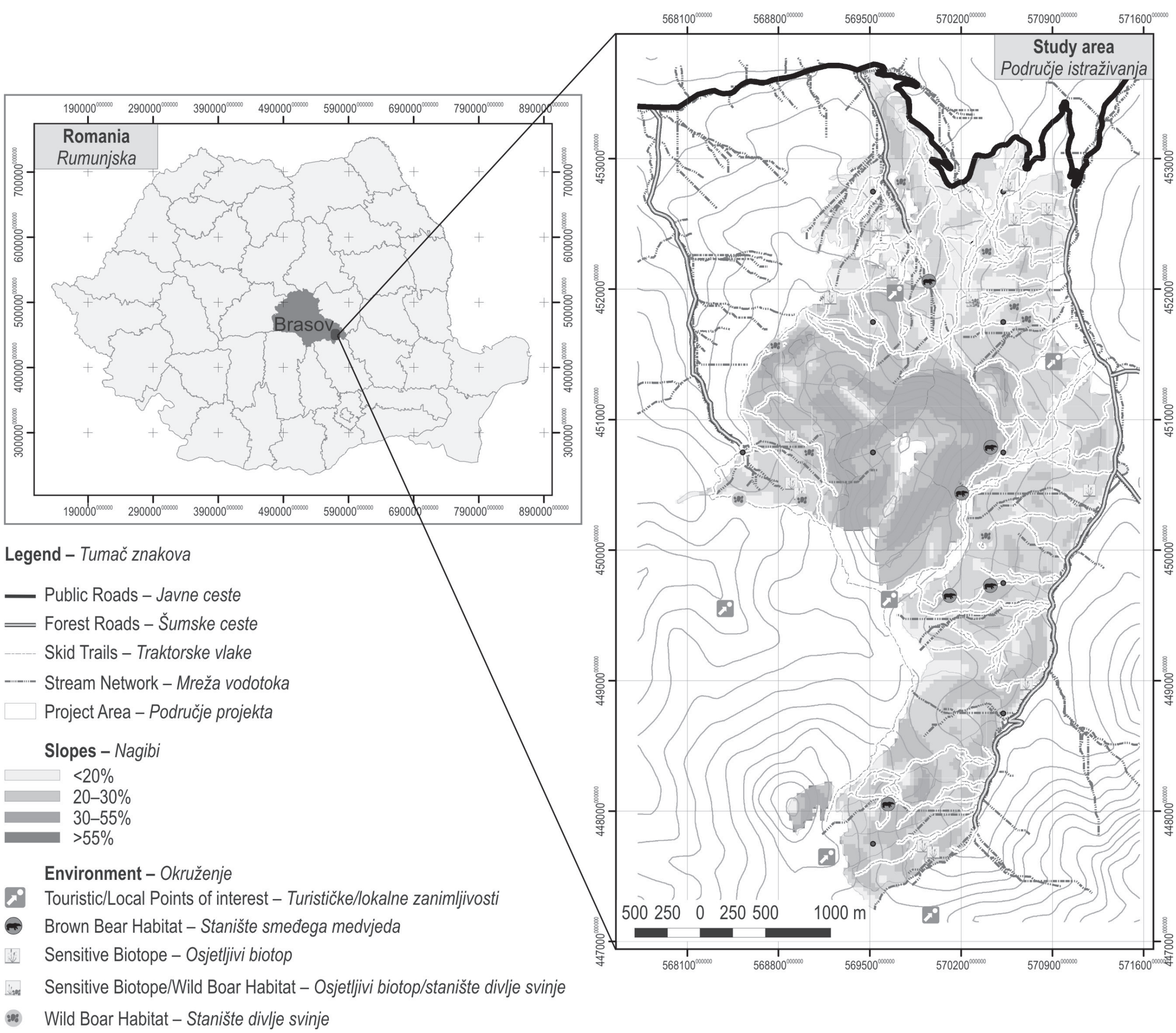


Fig. 3 Location of the study area, existing infrastructure and cardinal points (scenario Zero)

Slika 3. *Lokacija područja istraživanja, postojeća infrastruktura i ključna mjesta (nulta varijanta)* regarding the importance they gave to criteria and sub-criteria, as listed in Table 1. The preference weights were expressed on a ratio scale. The sum of preference weights for criteria had to be 100%. The preference weights given to sub-criteria of each criterion had also to sum 100%. The response rate in the survey was about 26% from the 103 successfully delivered survey forms to the stakeholders. The details regarding methodology and results of the stakeholder consultation were comprehensively presented in another study.

2.3 Study location – *Istraživano područje*

This study was conducted in a forest area of approximately 903 ha, located in Brasov County (45º55′ North Latitude and 25º90′ East Longitude), Romania (Fig. 3).

The forest is owned by the community of Tarlungeni and managed by Ciucas Autonomous Forest Administration. The forest is located at an altitude of 900–1600 m above sea level. According to the forest management plan, the most common forest types in this area are: mountain beech forests on shallow soils with mull flora; mixed fir-beech forests with mull flora of medium productivity; and beech forests with *Festuca altissima*. The geology is marly flysch, sandstones and massive conglomerates. The hydrological network includes permanent water streams, with maximum flow in spring and minimum in winter. Based on the Köppen classification presented in the forest management plan, the study area is part of the climatic province Dfck, characterized by a boreal climate (D) with precipitation varying between 750 mm and 1000 mm throughout the year (f), with average temperatures for at least three months >10ºC (c) and for at least four months >7ºC (k). The average annual temperature is 7.8ºC, the average number of days with a snow layer is 71 and the average number of days without frost is 173. One fifth of the studied forest area is located on gentle slopes (<20%), while approximately 10% is located on steep terrain (>55%). The annual allowable cut is about 4310 m^3. Other key figures are presented in Table 2.

Table 2 Key figures about study area
Tablica 2. *Glavni podaci o istraživanom području*

Forest area *Šumsko područje*	902.7 ha
Average growing stock *Prosječna drvna zaliha*	296.6 m^3/ha
Total annual growth *Ukupni godišnji prirast*	7 198 m^3
Total annual allowable cut (AAC) *Ukupni godišnji sječivi etat (GSE)*	4 308 m^3
AAC thinning *Proreda GSE-a*	1 120 m^3
AAC final cuts *Glavni prihod GSE-a*	3 188 m^3
Average timber price on stump *Prosječna cijena drva na panju*	25.3 €/m^3
Average timber price at road side *Prosječna cijena privučenoga drva*	42.6 €/m^3
Costs of felling-delimbing-sorting *Troškovi rušenja, kresanja, razvrstavanja*	7.0 €/m^3
Cleared road bed corridor width *Oduzeta širina za planum ceste*	12.0 m

2.4 Field survey – *Terenska mjerenja*

Field survey is a necessary stage prior to planning new forest roads and skid trails. Its purpose is to quantitatively and qualitatively evaluate the existing forest infrastructure. Data regarding quality of existing roads have been collected (e.g. damaged road bed, damaged bridges) and inspected elements have been categorized by causative factors. The geographic coordinates were recorded for each identified issue. In addition, a thorough survey of the project area was also performed, identifying and mapping cardinal points for road planning (i.e. possible locations of landing areas, good stream crossing points, ecologically important areas, touristic/local/cultural points of interest), while skidding trails have been mapped using a GPS for recording intervals of 5 seconds. Trails widths, stream crossings, skidding trail segments going entirely through water streams, soil erosion, average gradients and lengths of steep trails have been recorded in the data collection protocol.

For field data collection, the following instruments were used: GPS Garmin 60 CSx GPSMAP for recording geographic coordinates and for mapping skid trails network; Meridian clinometer for slope measurements; Handheld Algiz 7 rugged Tablet PC for the data collection protocol and a Laser LTI TruePulse 360 optic device for distance measurements. For data processing, ESRI® Arc GIS Desktop 10 and Microsoft Office Excel® were used.

2.5 Qualitative assessment of forest infrastructure *Kvalitativna procjena šumske infrastrukture*

This phase refers to the calculation of several structural indices of the forest road network (Pentek 2005; Bereziuc et al. 2008) based on the data from the field survey and GIS database: road density index, road distance, relative openness, geometric mean skidding distance and actual mean skidding distance. The last two indices have been derived both with analytic formulas and from analysis with ESRI® Arc GIS tools. In the latter case, the first hypothesis for deriving the geometric mean skidding distance was to assume that timber harvested from a forest management unit is concentrated into its centre of gravity and the skidding distance was calculated to these points. However, due to large sizes of management units, the accuracy of this method was very low. So, the assumption was used that harvested timber was concentrated at points located at 100 × 100 m from each other, thus resulting a grid of points based on which the mean skidding distance has been finally determined. In order to obtain the actual mean skidding distance, a correction factor was applied to mean skidding distance depending on local topography (kg). Studied literature (Segebaden 1964; Amzica 1971; Pentek 2005) mentioned correction factors varying between 1.05–1.70. For the purpose of this study, the correction factor kg was established to 1.50. Relative openness was calculated with classical formulas and by GIS analysis using the buffer method. Statistics regarding levels of forest accessibility were also performed. The automation of work flow processes was performed in Model Builder ™ extension from ESRI® ArcGIS Desktop 10. Structural indices of the skid trails network were derived in the same way as for the road network.

2.6 Assessment of harvesting systems – *Procjena sustava pridobivanja drva*

The most common harvesting methodology used in Romania is trunks and masts (Ciubotaru 1998), a method similar to the tree-length system in which trees are felled, topped and delimbed at the felling site and then extracted either as full trunks (masts) or as multiple of assortments at the road side. Extraction is usually done by winch tractors (U651) or skidders (TAF) manufactured in Romania. Pre-skidding is a specific operation in timber extraction for Romanian harvesting conditions with low density of forest roads and long skidding distances (Oprea et al. 2008). This is usually done by horse or ox harnesses at distances up to 150–200 m (Ciubotaru 1998), and refers to the transport of timber from stump to the closest skid trail. However, currently used harvesting systems in the study area are the TAF 657 skidder for final cuts and the winch tractor U651 for thinnings.

2.6.1 Assessment of productivity – *Procjena produktivnosti*

Productive system hour (PSH) is a parameter used in calculation of timber extraction costs. For the purpose of this study, productivity of harvesting systems was calculated as follows:

Since there were no specific local productivity models available, PSH of the U651 winch tractor was determined based on a logarithmic regression function derived from existing time norms (Ciubotaru 1996) that consider the following variables: group of tree species (i.e. coniferous, broadleaves), average tree volume and mean skidding distance.

PSH of the TAF 657 skidder was determined based on a recent local productivity model (Duta 2012), developed for hard-to-reach mountain regions, with similar topographic, site and infrastructure conditions as in this study.

2.6.2 Costs of harvesting systems – *Troškovi sustava pridobivanja drva*

The cost per system hour was calculated for the TAF 657 skidder and the U651 winch tractor using the FAO cost calculation scheme adapted by Holzleitner et al. (2011a), considering an interest rate of 6.5% and including the operator's costs. The input data used for calculations were the result of discussions with representatives of local forest administration.

2.6.3 Soil erosion and transport of sediments *Erozija tla i transport sedimenata*

Soil erosion and transport of sediments represent key issues in the study area. During the field survey, records were made of damages on residual stands due to timber skidding and areas with massive soil erosion (e.g. depths >150 cm) and sediment transport through water streams. Moreover, several segments of skid tracks were identified as going entirely through permanent water streams. A recent study in harvesting plots with similar site conditions (Sparchez et al. 2009) showed that most of the trees located in a buffer zone of 5 m along skid trails were damaged. An average value of soil dislocation of 40.5 m^3/ha was also reported, depending on the type of soil, harvesting method, average tree volume and local topography. In addition, Duta (2012) developed a model for quantifying soil erosion in timber skidding, based on soil type and slope grade of skid trails, reporting an average soil dislocation of 0.713 m^3 per running meter of skid trail.

2.6.4 CO_2 emissions – *Emisija CO_2*

The Kyoto Protocol calls for active action of all EU member states in reduction of greenhouse gas emissions (2002/358/CE). Under these circumstances, the impact of road construction, harvesting machinery and timber trucks on CO_2 emissions was evaluated for each infrastructure scenario. For determining the CO_2 emissions from timber transport, the assumptions were as follows: a CO_2 output factor for diesel engines of 2.65 kg/l, an average fuel consumption on forest roads of 2.05 l/km and a truck payload of 25 m^3 (Holzleitner et al. 2011b). Based on several studies on emissions from forest operations (Berg and Karjalainen 2003; Johnson et al. 2005; Markewitz 2006), the evaluation of CO_2 emissions from timber extraction was done considering a CO_2 output factor of 2.65 kg/l, PSHs of U651 winch tractor and TAF657 skidder, and fuel consumption rates of 7.5 l/h for the U651 winch tractor and 10.0 l/h for the TAF657 skidder.

Regarding road construction impact on CO_2 emissions, Loeffler et al. (2008) reported a rate of 3.8 t CO_2/km of forest road built in mixed profile on slopes with gradients less than 50%, for a CO_2 output factor of 2.73 kg/l of diesel. Karjalainen and Asikainen (1996) noted a value of 3.3 t CO_2/km for forests road built in Finland and for a CO_2 output factor of 2.66 kg/l.

2.7 Forest road scenarios – *Varijante šumskih cesta*

The focus of this paper was on the effect that enhancement of forest infrastructure alone had on the current management practices, without considering any changes in harvesting systems. However, the improvement of forest infrastructure created the conditions for adapting current timber extraction practices

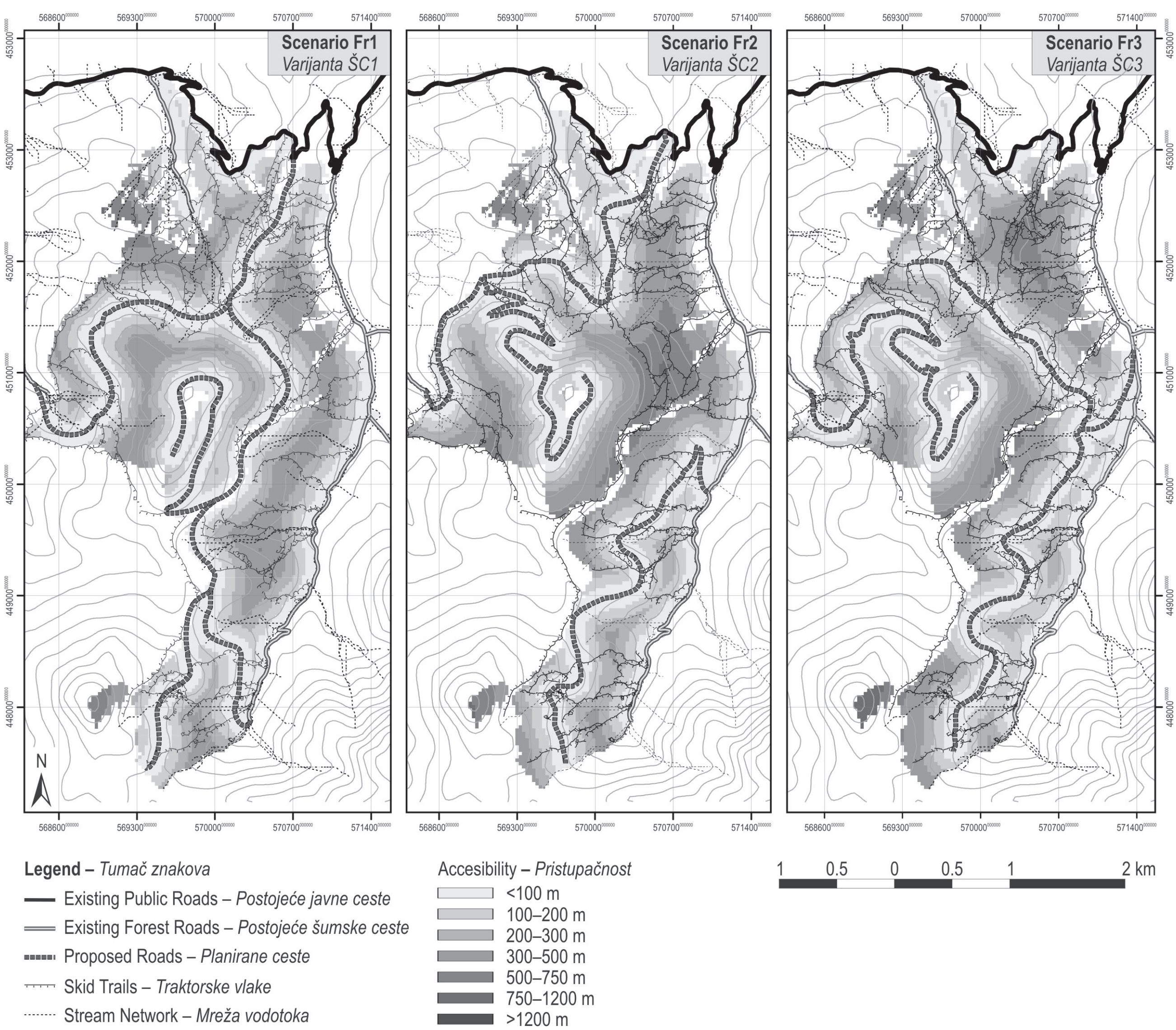


Fig. 4 Infrastructure scenarios proposing new forest roads (FR1–FR3)

Slika 4. *Infrastrukturne varijante predložene novim šumskim cestama (ŠC1–ŠC3)*

Table 3 Structural indices of forest infrastructure before and after planning new roads
Tablica 3. *Strukturni pokazatelji šumske infrastrukture prije i nakon planiranja novih cesta*

Structural indices *Strukturni pokazatelji*	Scenarios – *Varijante*			
	Zero – *Nulta*	FR1 – *ŠC1*	FR2 – *ŠC2*	FR3 – *ŠC3*
Length of road network, m *Duljina mreže cesta*, m	11 719	25 795	25 327	24 501
– out of which new forest roads, m – *od toga novih šumskih cesta*, m	–	14 076	13 608	12 782
Density index of road network, m/ha *Klasična otvorenost mreže cesta*, m/ha	13.0	28.6	28.1	27.2
Road distance, m *Razmak cesta*, m	770	350	356	368
Geometric mean skidding distance SD0, m *Geometrijska srednja udaljenost privlačenja SD0*, m	192	87	89	92
Mean skidding distance (grid 100 x 100), m *Srednja udaljenost privlačenja (mreža točaka 100 x 100)*, m	576	170	191	178
Maximum skidding distance (grid 100 x 100), m *Najveća udaljenost privlačenja ((mreža točaka 100 x 100)*, m	1 402	652	710	826
Actual mean skidding distance, m *Stvarna srednja udaljenost privlačenja*, m	864	255	287	268
Actual maximum skidding distance, m *Stvarna najveća udaljenost privlačenja*, m	2 104	978	1 065	1 238
Length of skid trails network, m *Duljina mreže šumskih vlaka*, m	71 301	67 121	67 349	69 939
Density index of skid trails network, m/ha *Klasična otvorenost mreže traktorskih vlaka*, m/ha	79.0	74.4	74.6	77.5

to state of the art harvesting systems. These issues will be addressed in a further study.

In order to test and validate the conceptual model, a Zero option (current infrastructure conditions) and other three infrastructure scenarios proposing new roads (FR1–FR3) were developed in GIS and considered for the assessment, assuming in all cases current harvesting and skidding means. The alternatives proposing new forest roads were mapped in ESRI® Arc GIS (Fig. 4), based on contour line maps derived from DEM, considering maximum slope grade of the road, terrain steepness and constraint layers developed from cardinal points collected during the field survey. The processes were automated in Model Builder™.

2.8 Cost evaluation of forest road scenarios *Troškovno vrednovanje varijanata šumskih cesta*

Since the proposed roads are intended to serve for low annual timber traffic (<1000 t), they were considered as a low category of secondary forest roads with mixed (fill-cut) cross profiles adapted to natural contour lines, road bed widths of 3.5 m, maximum slope grades of 13% for unloaded trucks and 9% for loaded trucks. According to Enescu (2011), adopting this type of forest road, with a gravel finishing adapted to a low timber traffic volume, could lead to a significant reduction of investment effort (between 20–33%). Therefore, considering Romanian average forest road construction costs of about 100 €/m, the unit construction cost for the study area was estimated to 70 €/m. Maintenance costs were estimated to 2 €/m p.a. for valley roads and 1 €/m p.a. for slope roads. The annuity of forest roads was calculated considering discounted total road construction costs (Pičman and Pentek 1996), for an interest rate of 6.5% and an investment life span of 30 years. Total yearly costs for each scenario were calculated as an algebraic sum of annuity, maintenance costs and discounted earnings from road bed clearance. However, only maintenance costs were

Table 4 Relative openness of the study area
Tablica 4. *Relativna otvorenost istraživanog područja*

Distance to road *Udaljenost do ceste*	Accessible forest area by scenario, % *Pristupačnost šumskomu području po varijantama*, %			
m	Zero – *Nulta*	FR1 – *ŠC1*	FR2 – *ŠC2*	FR3 – *ŠC3*
100	9%	35%	35%	35%
200	17%	62%	58%	62%
300	25%	82%	76%	79%
500	43%	99%	94%	96%
750	64%	100%	100%	99%
1 200	90%	–	–	100%
>1 200	100%	–	–	–

considered in scenario Zero, as the investment has already been paid off (road network older than 30 years).

For each infrastructure scenario, the total harvesting costs were calculated based on unit costs and PSH of each harvesting system. Incomes from timber sales were calculated in accordance with both timber selling procedures, on stump and at road side, based on prices provided by the local forest administration. In the end, the net profit-loss statement for each scenario and each procedure of timber sale was calculated.

3. Results – *Rezultati*

During the assessment process, scenario Zero was compared with the other scenarios (FR1–FR3) based on the specified criteria and sub-criteria weighted by stakeholders' preferences.

3.1 Qualitative assessment of infrastructure scenarios – *Kvalitativna procjena infrastrukturnih varijanata*

In scenario Zero, the access in study area is possible through two valley forest roads and one segment of a public road in total length of 11.72 km, which provide an uneven opening of forest stands. Scenarios FR1–FR3 propose between 12.8 km and 14.1 km of new forest roads (Table 3), improving the accessibility in the studied forest area. The road density increased from 13.0 m/ha (scenario Zero) to 27.2–28.6 m/ha (scenarios FR1–FR3), while the actual mean skidding distance reduced from 864 m (scenario Zero) to about 255–287 m (scenarios FR1–FR3). Thus, good premises for improving productivity and cost efficiency of harvesting systems were created.

A total of 71.3 km of skid trails were mapped during the field survey (scenario Zero). Most of the skid trails were developed on the line of the steepest slope alongside the stream or creek bed, causing massive soil erosion and transport of sediments, a common case being 1.0–1.5 m deep ravines. For scenarios FR1–FR3, the length of skid trails network decreased from 1.4 km to 4.2 km, depending on the case, due to possibilities of partial using of the existing skid trails in planning new roads (Table 3). Hence, the density index of secondary infrastructure ranges between 74.4 m/ha (scenario FR1) and 79.0 m/ha (scenario Zero).

The relative openness of the study area is presented in Table 4. In case of scenario Zero, about 43% of the area is accessible for buffer strip of 500 m from the roads, while approximately 90% is accessible for 1200 m buffer strip. Admittedly, in case of scenarios FR1–FR3, 94% to 99% of the forest area is accessible for a buffer strip of 500 m, while 58% to 62% is accessible for 300 m buffer strip.

3.2 Assessment of harvesting systems – *Procjena sustava pridobivanja drva*

Assessment of harvesting systems was performed in terms of productivity, costs and impact on the environment for each infrastructure scenario.

3.2.1 Productivity and costs – *Produktivnost i troškovi*

Productive system hour (PSH) of harvesting systems has significantly increased in scenarios FR1–FR3 proposing new roads (Fig. 5), when compared to the current infrastructure situation. PSH of the U651 winch tractor increased from 1.9 m^3/h (scenario Zero) to 3.0 m^3/h (scenarios FR1 and FR3), while the PSH of TAF 657 skid-

Table 5 CO_2 emissions from harvesting systems and timber transport
Tablica 5. *Emisija CO_2 od sustava pridobivanja drva i prijevoza drva*

Indicator *Pokazatelj*	Harvesting system *Sustav pridobivanja drva*	Scenario – *Varijanta*			
		Zero – *Nulta*	FR1 – *ŠC1*	FR2 – *ŠC2*	FR3 – *ŠC3*
CO_2 emissions, kg/m^3 Emisija CO_2, kg/m^3	Winch Tractor U651	11.5	7.2	7.4	7.2
	Skidder TAF 657	5.8	3.7	3.8	3.7
	Timber transport – *Prijevoz drva*	1.3	2.8	2.8	2.7

der improved from 7.5 m^3/h (scenario Zero) to 11.7 m^3/h (scenario FR1), triggering also important costs reductions in timber harvesting. Scenario FR1 had the lowest costs of timber extraction for both U651 tractor (8.9 €/m^3) and TAF657 skidder (5.4 €/m^3), when compared to other scenarios (Fig. 6). However, only minor differences were noticed between scenarios FR1–FR3.

3.2.2 Impact on the environment – *Utjecaj na okoliš*

Soil erosion could be limited by reducing the skidding distance and by closing several unnecessary skid trails. The values of dislocated soil due to timber skidding calculated according to Duta (2012) ranged between 47 858 m^3 (scenario FR1) and 50 838 m^3 (scenario Zero).

Table 6 Cost appraisal of infrastructure scenarios
Tablica 6. *Troškovna procjena infrastrukturnih varijanata*

Scenario – *Varijanta*	Zero – *Nulta*	FR1 – *ŠC1*	FR2 – *ŠC2*	FR3 – *ŠC3*
Road network length, m *Duljina mreže cesta*, m	11 719	25 795	25 327	24 501
– out of which new roads, m – *od toga novih cesta*, m	–	14 076	13 608	12 782
Construction cost, €/m *Troškovi izgradnje*, €/m	70			
Total construction costs, € *Ukupni troškovi izgradnje*, €	–	985 320	952 560	894 740
Annual interest rate, % *Godišnja kamatna stopa*, %	6.5			
Life span of investment, years *Životni vijek investicije*, godine	30			
Annuity road construction, € *Renta izgradnje cesta*, €	–	75 453	72 945	68 517
Maintenance costs, € *Troškovi održavanja*, €	23 438	31 655	31 187	30 361
Area of road clearance, ha *Površina oduzeta cestom*, ha	–	16.9	16.3	15.3
Volume from road clearance, m^3 *Volumen oduzet cestom*, m^3	–	5 009.3	4 842.8	4 548.8
Earnings from road bed clearance, € *Zarada od oduzete površine planuma ceste*, €	–	178 376	172 446	161 978
Discounted annual earnings road clearance, € *Godišnja zarada s popustom od oduzete površine ceste*, €	–	13 660	13 205	12 404
TOTAL ROAD COSTS, €/year *UKUPNI TROŠKOVI CESTA*, €/godini	23 438	93 448	90 926	86 474

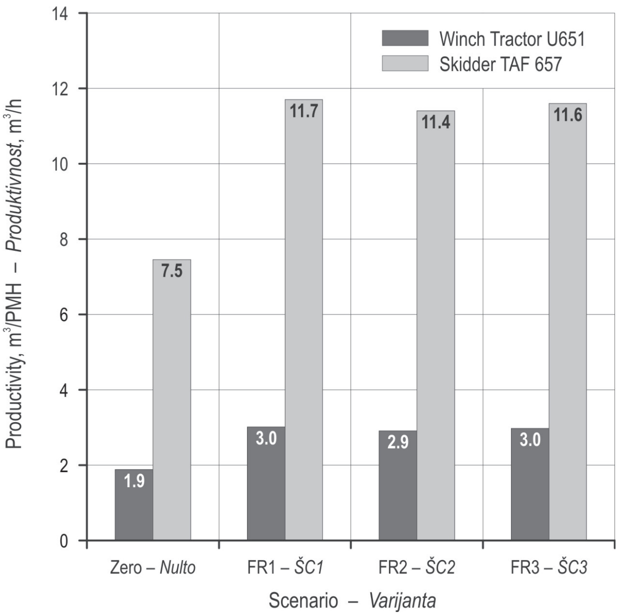


Fig. 5 Timber extraction productivity, by infrastructure scenario
Slika 5. *Produktivnost privlačenja drva po infrastrukturnim varijantama*

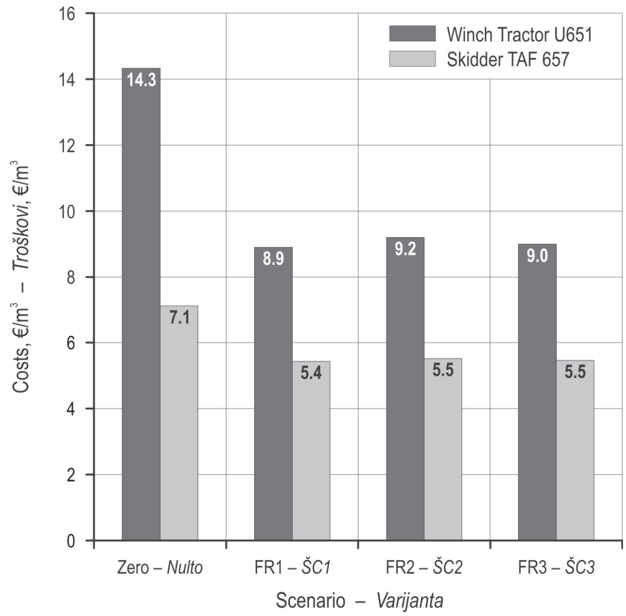


Fig. 6 Timber extraction costs, by infrastructure scenario
Slika 6. *Troškovi privlačenja drva po infrastrukturnim varijantama*

Due to improved infrastructure, a significant reduction in CO_2 emissions from harvesting systems could be achieved in scenarios FR1–FR3 (Table 5), from 11.5 kg CO_2/m^3 (scenario Zero) to 7.2 kg CO_2/m^3 (FR1 and FR3) in the case of the U651 tractor and from 5.8 kg CO_2/m^3 (scenario Zero) to 3.7 kg CO_2/m^3 (FR1 and FR3) in the case of the TAF657 skidder. Regarding CO_2 emissions due to timber transport inside the project area (Table 5), values range between 1.3 kg CO_2/m^3 (scenario Zero) and 2.8 kg CO_2/m^3 (scenario FR1).

3.3 Cost evaluation of forest road scenarios
Troškovno vrednovanje varijanata šumskih cesta

Total road cost is an indicator used in the overall utility evaluation of scenarios, with a relevant significance assigned by stakeholders. Therefore, cost analysis was conducted for all infrastructure scenarios (Table 6). The highest total road costs are required by scenario FR1 (93 448 € p.a.), while scenario Zero has the lowest costs (23 438 € p.a.). When considering only new roads, the lowest road cost scenario is FR3 (86 474 € p.a.).

Net profit-loss statements were calculated for all scenarios and each timber sales procedure (Table 7). First, in the case of timber sales on stump (current practice), the highest net profit was noted for scenario Zero (85 584 € p.a.), which did not involve any construction costs, while the lowest profit was attributed to scenario FR1 (15 574 € p.a.). However, it has to be underlined that all scenarios proposing new roads (FR1–FR3) were profitable. Second, when considering timber sales at the road side, the highest profit was recorded again in scenario Zero (91 300 € p.a.), while the lowest was noted in scenario FR1 (32 756 € p.a.). Scenarios FR1–FR3 proved again to be all profitable (Table 7). In addition, the contribution margin for harvesting operations increased from 1.33 €/m3 (scenario Zero) to 3.99 €/m3 (scenario FR1). Thus, in terms of their overall profit performance, it would be presumably better to change the selling procedure from stumpage to road side.

Provided that the current stumpage sales method is used, investment in new roads (FR1–FR3) would make no sense from the forest owner's point of view, since all profit would represent the forest contractors' profit. Therefore, investing in new forest infrastructure would only make sense if the timber sales procedures were replaced by selling timber at the road side. In this situation, the profits would be to the benefit of the forest owner. Furthermore, subsidies between 50% for private owned forests and 100% for local community forests are available for investing in forest infrastructure through EU Rural Development Programme (MARD 2012). Thus, contribution margin of forest administration could increase from 21.2 €/m^3 (scenario Zero) up to 25.1 €/m^3 (scenario FR1) (Table 7).

Table 7 Profit and loss statement by infrastructure scenarios
Tablica 7. *Dobit i gubitak po infrastrukturnim varijantama*

	Scenario – *Varijanta*			
	Zero – *Nulta*	FR1 – *ŠC1*	FR2 – *ŠC2*	FR3 – *ŠC3*
Timber felling-delimbing-sorting, € *Rušenje, kresanje, razvrstavanje drva, €*	30153			
Timber extraction cost, € *Troškovi privlačenja drva, €*	38 647	27 180	27 835	27 611
Savings timber extraction, € *Uštede pri privlačenju drva, €*	–	11 467	10 812	11 036
Net income timber sales on stump, € *Neto prihod od prodaje drva na panju, €*	109 022			
Income timber sales at the road side, € *Prihodi od prodaje privučenoga drva, €*	183 537			
Net income timber sales at the road side, € *Neto prihod od prodaje privučenoga drva, €*	114 738	126 204	125 549	125 773
Total road costs, €/year *Ukupni troškovi cesta,* €/godini	–23 438	–93 448	–90 926	–86 474
Total road costs (€/year) with EU incentives *Ukupni troškovi cesta (€/godini) s poticajima EU-a*	–23 438	–17 995	–17 981	–17 957
NET PROFIT-LOSS STATEMENT – *NETO DOBIT I GUBITAK*				
Timber sales on stump, €/year *Prodaja drva na panju,* €/godini	85 584	15 574	18 097	22 549
Timber sales at road side, €/year *Prodaja privučenoga drva,* €/godini	91 300	32 756	34 624	39 300
Timber sales at road side and EU incentives, €/year *Prodaja privučenoga drva i poticaji EU-a,* €/godini	91 300	108 209	107 568	107 817
TOTAL CONTTRIBUTION MARGIN FOR FOREST ADMINISTRATION *UKUPNA KONTRIBUCIJSKA MARŽA ZA UŠP*				
Timber sales on stump, €/m^3 *Prodaja drva na panju,* €/m^3	19.87	3.62	4.20	5.23
Timber sales at road side, €/m^3 *Prodaja privučenoga drva,* €/m^3	21.20	7.60	8.04	9.12
Timber sales at road side and EU incentives, €/m^3 *Prodaja privučenoga drva i poticaji EU-a,* €/m^3	21.20	25.12	24.97	25.03

3.4 Utility analysis and decision making – *Analiza korisnosti i odlučivanje*

Based on stakeholders' preferences regarding the importance of defined criteria and sub-criteria, the overall utility value of each scenario was calculated (Table 8). Stakeholders' consultation showed that the most important sub-criteria were: accessibility for performing silvicultural operations (20%), protection of ecologically important areas (14%) and road construction costs (11%). The least important one was the accessibility for touristic, local or cultural points of interest (1%). According to MAUT, the best alternative is the one with the highest score in total. With a total score of 0.682, scenario FR3 is the alternative that would best satisfy stakeholders' preferences and thus it would be recommended for implementation (Fig. 7).

The decision support tool for evaluating forest road alternatives presented in this study was tested and

Table 8 Multiple utility analysis of infrastructure scenarios
Tablica 8. *Višestruka analiza korisnosti infrastrukturnih varijanata*

Final scoring of alternatives – *Konačno bodovanje varijanata*										
Code *Šifra*	Criteria *Kriterij*	Weight *Važnost*	SCENARIO – *Varijanta*							
			Zero – *Nulta*		FR1 – *ŠC1*		FR2 – *ŠC2*		FR3 – *ŠC3*	
			UUV	WUV	UUV	WUV	UUV	WUV	UUV	WUV
A1	Neighbors independence *Neovisnost o susjedstvu*	8%	1.0	0.079	1.0	0.079	1.0	0.079	1.0	0.079
A2	Accessibility for forest operations *Pristupačnost za šumske poslove*	20%	0.0	0.000	1.0	0.201	0.9	0.179	1.0	0.192
A3	Accessibility for game management *Pristupačnost za lovno gospodarenje*	4%	0.0	0.000	1.0	0.045	0.9	0.041	0.8	0.034
A4	Loss of productive land (road clearance) *Gubitak šumskoga zemljišta (širina ceste)*	5%	1.0	0.049	0.0	0.000	0.0	0.002	0.1	0.004
B1	Construction costs *Troškovi gradnje*	11%	1.0	0.110	0.6	0.067	0.7	0.074	0.8	0.086
B2	Maintenance costs *Troškovi održavanja*	7%	1.0	0.070	0.0	0.000	0.1	0.004	0.2	0.011
B3	Harvesting costs *Troškovi pridobivanja drva*	8%	0.0	0.000	1.0	0.078	0.9	0.073	1.0	0.075
C1	Protection of ecologically valuable areas *Zaštita ekološki vrijednih područja*	14%	1.0	0.143	0.0	0.000	0.2	0.027	0.2	0.027
C2	CO_2 emissions – *Emisija CO_2*	5%	0.0	0.000	0.9	0.043	0.8	0.040	1.0	0.047
C3	Visual disturbance due to Curves/Intersections *Vizualni poremećaj zbog krivina i raskrižja*	6%	1.0	0.057	0.3	0.014	0.0	0.000	0.3	0.019
D1	Fewer accidents with personal injuries *Manji broj nesreća s osobnim ozljedama*	3%	0.0	0.000	0.9	0.025	0.7	0.021	1.0	0.029
D2	Risks of soil erosions and/or landslides *Rizik od erozije tla ili klizišta*	3%	0.0	0.000	1.0	0.026	0.6	0.017	0.7	0.018
D3	Accessibility for touristic/local/cultural interest *Pristupačnost za turističke, lokalne, kulturne interese*	1%	0.0	0.000	1.0	0.026	0.8	0.017	0.8	0.018
D4	Accessibility in case of forest fires *Pristupačnost u slučaju požara*	3%	0.0	0.000	1.0	0.013	0.9	0.011	1.0	0.010
D5	Accessibility in case of wind-throws/snow *Pristupačnost u slučaju vjetroizvala i snjegoloma*	2%	0.0	0.000	1.0	0.033	0.9	0.030	1.0	0.033
Total score – *Ukupni rezultat*		100%	6.0	0.507	10.6	0.651	9.5	0.614	10.6	0.682

* UUV - unweight utility values – *neponderirane vrijednosti korisnosti;* WUV – weighted utility values – *ponderirane vrijednosti korisnosti*

validated based on a participatory process. Considering multiple stakeholders' interests, all scenarios proposing new roads (FR1–FR3) performed better in overall terms than scenario Zero. Based only on normalized utility values of each sub-criterion (before weighting each sub-criterion with stakeholders' preferences), the total scoring showed that scenarios FR1 and FR3 were ranked equal first (Table 8). When stakeholders' preferences were considered, FR3 was the best performing scenario. Thus, it could be concluded that stakeholders' preferences do have significant importance. Therefore, sensitive analyses were conducted in order to show how changes in stakeholders' preferences for specific criteria or sub-criteria could affect the final

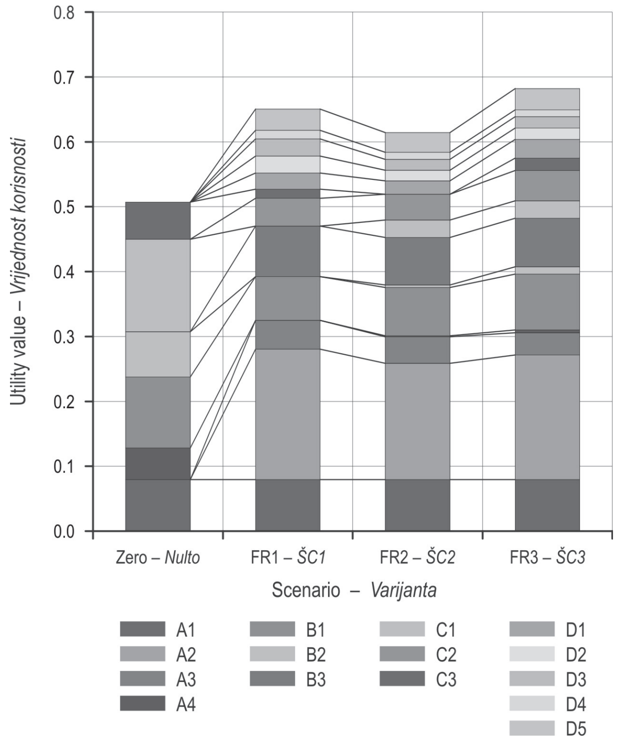


Fig. 7 Final score of scenarios after multiple utility analyses, based on sub-criteria A1–D5

Slika 7. *Konačni rezultati varijanata nakon višestruke analize korisnosti, temeljene na potkriterijima A1–D5*

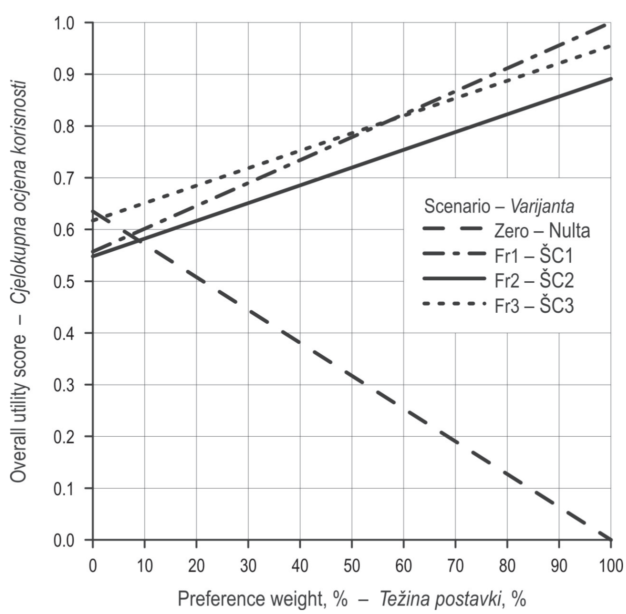


Fig. 8 Sensitive analysis regarding performance of accessibility for forest operations sub-criterion

Slika 8. *Osjetljiva analiza o djelovanju potkriterija pristupačnost za šumske poslove*

results. As an example, the sensitivity analysis regarding accessibility for forest operations sub-criterion was performed. Fig. 8 shows that scenario FR3 would perform best for preference weights up to 60% given to this sub-criterion. If the preference weight were above 60%, than scenario FR1 would be recommended for implementation. Regardless the preference given by the stakeholders to this sub-criterion, scenario Zero had the lowest score. Similarly, sensitivity analyses could be performed for all other criteria and sub-criteria.

4. Discussions and conclusions – *Rasprava i zaključci*

The aim of this study was to develop a decision support tool for evaluating different forest road options before technical design, using a participatory approach and multiple criteria analyses. Based on clearly defined criteria and sub-criteria, qualitative and quantitative assessments of forest infrastructure scenarios were performed. The conceptual model of the decision support tool showed a clear flow of processes and how the evaluation of forest road options could be done. The main processes refer to locating new roads, assessment of productivity and appraisal of cost efficiency in timber extraction, evaluation of impact on the environment and finally, the utility analysis of infrastructure scenarios. The model was tested and validated in a mountainous forest located in Romania. A suitable road variant based on stakeholders' preferences was recommended for implementation. Thus, the importance of the preliminary planning and assessment phase in forest road engineering was highlighted.

The multiple attribute utility theory (MAUT) proved to be an appropriate tool for evaluating forest road alternatives because, among others, it also allowed sensitivity analyses regarding the importance of stakeholders' preferences in the final score of alternatives. In comparison to the analytic hierarchy process (AHP) used by Coulter (2004), which is a more complex tool requiring expert judgments based on pairwise comparisons, MAUT was preferred in this study for its simplicity in use and its proven practicality in the development of decision support tools in the forestry sector (Lexer et al. 2005; Kangas et al. 2008). In addition, this study continued and extended the work of Zarojanu (2006; 2007), comprehensively and soundly addressing the economic, ecological and social aspects in selecting the most suitable forest road option, as recommended in the literature by Dürrstein (1998) and Heinimann (1998). Thus, this model proved its utility for supporting decision making in forest road engineering and could be used in other regions with similar topographic, forest site and social-cultural conditions. The decision support tool presented in this study could be improved by further process automation and by extending it with the assessment of the impact of new harvesting systems that could be introduced in the study area in the overall utility analysis of the infrastructure scenarios.

Acknowledgements – *Zahvala*

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), ID76945 financed from the European Social Fund and by the Romanian Government.

5. References – *Literatura*

Akay, A. E., Karas, J. R., Sessions, J., Yuksel, A., Bozali, N., Gundogan, R., 2004: Using high resolution digital elevation model for computer aided forest road design. Proceedings of International Society for Photogrammetry and Remote Sensing Congress Istanbul 2004 VII(B7): 1682–1750.

Akay, A. E., Sessions, J., 2005: Applying the Decision Support System TRACER to Forest Road Design. Western Journal of Applied Forestry 20(3): 184–191(8).

Amzica, A., 1971: Contributii la studiul desimii optime a retelei de drumuri auto forestiere din Romania. [Contributions to the study of the optimum forest road network density in Romania]. PhD Dissertation. Polytechnic Institute of Brasov, Faculty of Forestry, 246 p.

Aruga, K., 2005: Tabu search optimization of horizontal and vertical alignments of forest roads. Journal of Forest Research 10(4): 275–284.

Bereziuc, R., Alexandru, V., Ionescu, M., 2003: Eficiența economică a programării şi urmăririi automate a lucrărilor în execuția drumurilor forestiere (Economic efficiency of scheduling and automated follow-up of works in forest road construction). Bucovina Forestiera XI(1): 3–11.

Bereziuc, R., Alexandru, V., Ciobanu, V., Ignea, Gh., 2008: Elemente pentru fundamentarea normativului de proiectare a drumurilor forestiere (Elements for the substantiation of the normative of forest roads designing). Transilvania University of Brasov Publishing House, 393 p.

Berg, S., Karjalainen, T., 2003: Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry 76(3): 271–284.

Ciobanu, V. D., Alexandru, V., Borz, S. A., Mihaila, M., Dumitrascu, A. E., 2011: Calculus and evaluation methods for forest roads execution impact upon the environment. International Journal of Energy and Environment 5(5): 686–693.

Ciubotaru, A., 1996: Elemente de proiectare si organizare a exploatarii padurilor (Elements of designing and organizing timber harvesting). Lux Libris Publishing House, Braşov, 234 p.

Ciubotaru, A., 1998: Exploatarea padurilor (Timber harvesting), Lux Libris Publishing House, Braşov, 351 p.

Coulter, E. D., 2004: Setting forest road maintenance and upgrade priorities based on environmental effects and expert judgment. PhD Dissertation, Oregon State University Corvallis, 199 p.

Duta, I., 2012: Researches on wood collection in hard-to-reach mountain regions under specific conditions of Soveja III Production Unit, Vrancea County. PhD Thesis, Transilvania University of Brasov, Faculty of Silviculture and Forest Engineering, 189 p.

Dürrstein, H., 1998: Opening up of a mountainous region – decision making by integration of the parties concerned applying cost efficiency analysis, Proceedings of the FAO – Seminar on Environmentally Sound Forest Roads and Wood Transport, Sinaia, Romania.

Enache, A., Ciobanu, V. D., Pertlik, E., 2012: Approaches regarding environmental impact assessment of forest roads with a special emphasis on Romanian forestry sector. Bulletin of the Transilvania University of Brasov. Series II – Forestry. Wood industry. Agricultural food engineering 5(54): 63–72.

Enescu, A. H., 2011: Research about the usefulness and economic efficiency of forest transport network development, in the mountain area, with summary arranged roads and their characteristics. PhD Thesis, Transilvania University of Brasov, Faculty of Silviculture and Forest Engineering.

Greene, R., Luther, J. E., Devillers, R., Eddy, B., 2010: An approach to GIS-based multiple criteria decision analysis that integrates exploration and evaluation phases: Case study in a forest – dominated landscape. Forest Ecology and Management 260(12): 2102–2114.

Gumus, S., Acar, H. H., Toksoy, D., 2008: Functional forest road network planning by consideration of environmental impact assessment for wood harvesting. Environmental Monitoring and Assessment 142(1–3): 109–116.

Heinimann, H., 1998: Oppening up planning taking into account environmental and social integrity. Proceedings of the FAO – Seminar on Environmentally Sound Forest Roads and Wood Transport, Sinaia, Romania.

Holzleitner, F., Stampfer, K., Visser, R., 2011a: Utilization rates and cost factors in timber harvesting based on long-term machine data. Croatian Journal of Forest Engineering 32(2): 501–508.

Holzleitner, F., Kanzian, C., Stampfer, K., 2011b: Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. European Journal of Forest Research 130(2): 293–301.

Johnson, L. R., Lippke, B., Marshall, J. D., Comnick, J., 2005: Life-cycle impacts of forest resource activities in the Pacific

Northwest and Southeast United States. Wood and Fibre Sciences 37 (Corrim Special Issue): 30–46.

Karjalainen, T., Asikainen, A., 1996: Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 69(3): 215–228.

Kangas, A., Kangas, J., Kurttila, M., 2008: Decision support for forest management. Springer Science + Business Media B.V., 223 p.

Kühmaier, M., Stampfer, K., 2010: Development of a Multi-Attribute Spatial Decision Support System in Selecting Timber Harvesting Systems. Croatian Journal of Forest Engineering 31(2): 75–88.

Lexer, M. J., Vacik, H., Palmetzhofer, D., Oitzinger, G., 2005: A decision support tool to improve forestry extensions service for small private forest owners in southern Austria. Computers and Electronics in Agriculture 49: 81–102.

Loeffler, D., Jones, G., Vonessen, N., Healey, S., Chung, W., 2008: Estimating Diesel Fuel Consumption and Carbon Dioxide Emissions from Forest Road Construction. In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008, 11 p.

Markewitz, D., 2006: Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. Forest Ecology and Management 236(2–3): 153–161.

Oprea, I., Derczeni, R., Iordache, E., Giannoulas, V.J., 2008: Technological lines for logging in reduced accessibility conditions. Bulletin of the Transilvania University of Brasov, Series II – Forestry. Wood industry. Agricultural food engineering 1(50): 21–24.

Pentek, T., Picman, D., Potocnik, I., et al., 2005: Analysis of an existing forest road network. Croatian Journal of Forest Engineering 26(1): 39–50.

Pentek, T., Nevecerel, H., Picman, D., Porsinsky, T., 2007: Forest road network in the Republic of Croatia - Status and perspectives, Croatian Journal of Forest Engineering 28(1): 93–106.

Picman, D., Pentek, T., 1996: The influence of forest roads building and their maintenance costs on their optimum density in low lying forests of Croatia. In: Proceedings of the FAO – Seminar on Environmentally Sound Forest Roads and Wood Transport, Sinaia, Romania.

Popovici, V., Bereziuc, R., Clinciu, I., 2003: Extinderea retelei de drumuri pentru accesibilizarea fondului forestier si, in general, a padurii (Extension of road network for improving the access to forests and forest fund). Bucovina Forestiera XI(2): 36–40.

Rogers, L., 2005: Automating contour-based route projection for preliminary forest road designs using GIS. Master Thesis. University of Washington, 87 p.

Segebaden, G., 1964: Studies of cross-country transport distances and road net extension. Studia Forestalia Suecica 18, 69 p.

Spârchez, Gh., Derczeni, R., Iordache, E., Drosos, V., 2009: The impact of different carriages on soil and trees during skidding in the Romanian forests. Bulletin of the Transilvania University of Brasov, Series II - Forestry, Wood industry and Agricultural food engineering 2(51): 35–44.

Stampfer, K., 2007: Harvesting Systems for Mountainous Regions – Course Script. Institute of Forest Engineering, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences - BOKU, Vienna.

Stuckelberger, J., A., 2007: A weighted-graph optimization approach for automatic location of forest road networks. PhD Dissertation, Vdf Hochschulverlag AG an der ETH, Zürich.

Zarojanu, D., Duduman, G., 2006: Consideratii privind stabilirea traseelor de drumuri forestiere (Considerations regarding the establishment of forest road routes). Revista Padurilor 121(6): 46–49.

Zarojanu, D., 2007: Drumuri Forestiere (Forest Roads). University of Suceava Publishing House, 258 p.

Legislation and Policies:

2002/358/CE: Council Decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments hereunder.

World Wide Web sites:

Ministry of Agriculture and Rural Development - MARD (2012): European Agricultural Fund for Rural Development (2007–2013), <http://www.madr.ro/pages/page.php?self=03&sub=0302&tz=030201>, accessed on 15.09.2012.

Ministry of Environment and Forests, 2011a: The policy and strategy for the development of Romanian forestry sector (2001-2010), <http://www.mmediu.ro/paduri/politici_forestiere.htm>, accessed on 07.12.2011.

Ministry of Environment and Forests (2011b): State of Romanian forests - 2010, <http://www.mmediu.ro/paduri/management_forestier.htm>, accessed on 07.12.2011.

Ministry of Environment and Forests, 2012: Normative PD-003-11 regarding designing of forest roads, <http://www.mmediu.ro/beta/wp-content/uploads/2012/08/2012-08-07_paduri_normativproiectaredrumuriforest.pdf>, accessed on 15.09.2012.

Sažetak

Integracijski alat za odlučivanje pri procjeni varijanata šumskih cesta u planinskom području Rumunjske

Razuman je razvoj šumske infrastrukture okosnica za održivo gospodarenje šumama. Međutim, današnje planiranje šumskih prometnica mora ispuniti više sukobljenih ciljeva, što nije jednostavan zadatak. Model temeljen na GIS-u razvijen je za potporu odlučivanja u inženjeringu šumskih cesta. Alat dopušta procjenu šumskih infrastrukturnih varijanata na temelju analize različitih kriterija s obzirom na interese sudionika, gospodarske, ekološke i socijalne aspekte. Prvo, problem pri odlučivanju jasno je strukturiran, a zatim su ponderirani kriteriji i potkriteriji. Nakon toga su definirane varijante šumskih cesta te su izvedene kvantitativne i kvalitativne procjene infrastrukture i sustava pridobivanja drva. Na kraju je provedena analiza korisnosti za svaku varijantu; varijanta šumske ceste s najvišom ocjenom korisnosti odabrana je kao najprikladnije rješenje za provedbu. Model je provjeren i potvrđen u planinskom šumskom području županije Braşov u Rumunjskoj. Šumsko se područje nalazi na nadmorskoj visini od 900 do 1600 m. Jedna petina promatranoga šumskoga područja nalazi se na blagim padinama (<20 %), dok se oko 10 % nalazi na strmom terenu (>55 %). Postignuto je smanjenje srednje udaljenosti privlačenja s 864 m na 255 – 268 m, što dovodi do povećanja produktivnosti privlačenja sa 7,5 m^3/h na 11,7 m^3/h te do povećanja kontribucijske marže s 21,2 €/m^3 na 25,1 €/m^3. Unapređenje šumske infrastrukture smanjuje emisiju CO_2 prilikom privlačenja drva i transporta s 8,52 kg/m^3 na 7,3 kg/m^3. Ovo istraživanje pokazuje kako se multikriterijska analiza korisnosti može upotrijebiti u procjeni različitih varijanata šumskih cesta temeljenih na zajedničkom pristupu. Multikriterijska analiza korisnosti (MAUT) pokazala se kao prikladno sredstvo za procjenu varijanata šumske ceste jer, među ostalim, uključuje analizu osjetljivosti s obzirom na preferencije sudionika u konačni rezultat varijanata. Alat za podršku odlučivanju prikazan u ovom istraživanju može biti poboljšan daljnjim procesom automatizacije i njegovim proširenjem za nove sustave privlačenja koji bi mogli biti uključeni u područje istraživanja.

Ključne riječi: šumske ceste, multikriterijsko odlučivanje, analiza korisnosti, alat za odlučivanje, zajednički pristup

Authors' address – *Adresa autorâ*:

Adrian Enache, MSc.*
e-mail: adrian.enache@unitbv.ro
Prof. Valentina Doina Ciobanu, PhD.
e-mail: ciobanudv@unitbv.ro
Transilvania University of Brasov
Department of Forest Engineering
Forest Management Planning and Terrestrial Measurements
Sirul Beethoven 1
500123, Brasov
ROMANIA

Martin Kühmaier, PhD.
e-mail: martin.kuehmaier@boku.ac.at
Prof. Karl Stampfer, PhD.
e-mail: karl.stampfer@boku.ac.at
University of Natural Resources and Applied Life Sciences Vienna
Department of Forest and Soil Sciences
Institute of Forest Engineering
Peter Jordan Straße 82
A-1190 Vienna
AUSTRIA

* Corresponding author – *Glavni autor*

Received (*Primljeno*): December 12, 2012
Accepted (*Prihvaćeno*): April 10, 2013

Publication III

Accepted 15th November 2014 – published online and print

Environmental Engineering and Management Journal June 2015, Vol.14, No. 6, 1409-1421
http://omicron.ch.tuiasi.ro/EEMJ/

"Gheorghe Asachi" Technical University of Iasi, Romania

STAKEHOLDERS' PERCEPTIONS REGARDING EVALUATION CRITERIA OF FOREST ROAD OPTIONS IN ROMANIA

Adrian Enache[1,2]*, Valentina Doina Ciobanu[2], Karl Stampfer[1]

[1]Institute of Forest Engineering, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences – BOKU, Peter-Jordan-Straße, 82, A-1190, Vienna, Austria
[2]Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Transilvania University of Brasov, 1 Şirul Beethoven, 500123, Braşov, Romania

Abstract

Transparent and participatory decision making in solving complex forest management problems are fostered by numerous forest policies. Thus, all relevant stakeholders should be involved in the process of evaluating forest road options from the early stages of planning. However, participatory tools are not yet used as a matter of course in the Romanian forest sector. This study aimed to stress the importance of corporate social responsibility (CSR) in decision making in the forest sector. A survey (n=27) was conducted for prioritizing stakeholders' preferences on criteria and sub-criteria used in the assessment of forest road options. ANOVA and post-hoc tests were performed for analysing the statistical significance of responses and possible patterns of stakeholders' behaviour. Accessibility for performing forest works, protection of ecologically important areas and road construction costs were identified as the most relevant evaluation sub-criteria. The results showed stakeholders are aware of the environmental impacts of forest roads, while they show yet little concern for risks of accidents and other social factors. In respect to certain criteria, a tendency of homogenous clustering of expertise groups' opinions was noted, the groups with forestry backgrounds behaving differently than those with environmental or tourism backgrounds. The outcomes of this study are useful for practitioners willing to approach complex decision problems like forest road network planning or selection of timber harvesting systems from a multidimensional perspective.

Key words: corporate social responsibility, decision support, forest roads, forest operations, multiple criteria decision making

Received: January, 2014; Revised final: October, 2014; Accepted: November, 2014

1. Introduction

Romanian forests cover 6.65 million ha (World Bank, 2012) and they have one of the lowest road density in Europe, about 6.5 m/ha (Enescu, 2011). Skidding represents the main method of timber extraction using winch tractors and skidders, horse harnesses or gravitational hauling, while state of the art harvesting systems including forwarders and cable yarders are used below their capacity, specifically due to the lack of access. The productivity and efficiency in forest operations is very low, while the environmental footprint of forest operations is relatively high (i.e. soil erosion; transport of sediments; residual stand damage) due to the long extraction distance.

Forest road networks are the backbone of sustainable forest management (SFM). They provide better access to forest resources, for tending, maintenance and harvesting operations (Abrudan et al., 2009). However, non-state forest owners, which own about 50% of the Romanian forests, perceive forestry as a profit based activity which provides an immediate source of income rather than a long term investment and commitment (Abrudan, 2012). Hence, in terms of forest infrastructure development, they are mostly focused on solving immediate accessibility problems to forest stands which are at

* Author to whom all correspondence should be addressed: e-mail: adrian.enache@boku.ac.at; Phone: +43-1-47654-4311

harvesting age, disregarding the long term benefits of thorough and integrative road network planning based on sustainability principles. In this context, multiple criteria decision making (MCDM) tools have not yet been used in solving complex forest management problems in Romania, such as the benchmarking of different variants and selection of the most suitable forest road option for specific local conditions.

Planning and building forest roads in Romania is done mainly based on technical economic aspects, the share allocated for environmental and social aspects in decision making being rather low. Participatory approaches in decision making are not used as a matter of course in forest management. Nevertheless, the technical, economic, environmental and social aspects of forest roads and their multiple uses should be considered simultaneously from the early stages of forestry planning by consulting all relevant stakeholders (Widhalm et al., 2005). Although the new normative regarding the designing of forest roads (MENVF, 2012) gives a stronger consideration to environmental aspects, the issues related to stakeholder involvement are still missing. Thus, for the sustainable management of the Romanian forests it is necessary to enhance the forest infrastructure through a more efficient and effective planning of road networks, fostering the use of remote sensing techniques, GIS and MCDM tools.

European and national forest policies advocate good governance, including transparency and active stakeholder involvement in the decision making process for increasing the likelihood of the lasting provision of goods and services through SFM (EC, 2013; EU, 2010; FAO, 2010; Forest Europe, 2011; MENVF, 2011). In this context, corporate social responsibility (CSR) could foster the implementation of good governance and sustainability principles in forest management. Glavas and Godwin (2013) argued the important role of stakeholders' perception in CSR, underlining that enterprises should engage in ethical, legal, economic and philanthropic dimensions of CSR for all their key stakeholders and the natural environment in order to be considered socially responsible. In turn, Costa and Menichini (2013) developed a multi-criteria approach combined with fuzzy logic to evaluate CSR through stakeholder perception, highlighting that perception of an enterprise CSR commitment is strictly linked to the public recognition of the socially responsible behaviour of the respective enterprise. In the forestry sector, Matilainen (2013) stressed forest certification is a significant CSR initiative, while Gordon et al. (2012) showed the commonalities between CSR and SFM, mentioning that forest stakeholders should include employees, contractors, regulators, local councils and environmental nongovernmental organisations (ENGOs). Within this framework, development of forest infrastructure should also have a strong CSR dimension.

Numerous scientific papers have been published in the last decade regarding the use of MCDM tools and group decision making (GDM) in forest management (Ferrario et al., 2014; Green et al., 2010; Kangas and Kangas, 2005; Kühmaier and Stampfer, 2010; Lexer et al., 2005; Mendoza and Prabhu, 2000; Sheppard and Meitner, 2005; Wolfslehner and Vacik, 2008; Wolfslehner et al., 2011). The methodological approaches of these studies could also be applied in the Romanian forest sector in solving complex decision problems, including the selection of the most suitable forest road options. Diaz-Balteiro and Romero (2008), Kangas et al. (2008) and Ananda and Herath (2009) presented comprehensive literature reviews, identifying and describing several MCDM methods that have been tested and applied in forest management. Out of these, the most commonly used approach for dealing with risk and uncertainty in forestry is the multiple attribute utility theory - MAUT (Diaz-Balteiro and Romero, 2008), which was also the focus of our study. It should be noted that prioritizing the preferences of evaluation criteria and indicators is an important part of the MAUT.

Building forest roads in Romania requires a considerable amount of approvals and authorizations from different authorities with limited knowledge and experience in the field of sustainable forest management (Abrudan, 2012). Since this fact generally hinders the construction of the roads for months or even years, the core idea of our approach was that by involving all relevant stakeholders in the decision making process from the earliest phase of road planning, the transparency of the process could be increased and the decision makers could better understand and assess the pros and cons of each road option. Thus, benchmarking several options of forest roads based on a multiple criteria analysis and not only technical-economic principles prior to technical designing could reduce the level of bureaucracy in obtaining the necessary approvals for road construction.

In pursuing our goal to increase the corporate social responsibility in the Romanian forestry sector and to facilitate the utilization of MCDM in forest management, and especially in road network planning, the purpose of this study was firstly to define and weigh a set of criteria and sub-criteria for the benchmarking of forest roads options through a stakeholder consultation and, secondly, to evaluate the relevant stakeholder groups' opinions regarding these assessment criteria and sub-criteria.

2. Material and methods

2.1. Problem structuring

Problem structuring and identifying decision makers' preferences in respect to evaluation criteria or decision alternatives are prerequisites for any decision support process. The Romanian normative (MENVF, 2012) foresees the technical-economic assessment of several forest road variants prior to the selection of the final option for which a technical project must be designed. Thus, the decision problem in our study was the selection of the most suitable forest road option from a multidimensional perspective, according to stakeholders' interests. Mingers and Rosenhead (2004) underlined that the characteristic *modus operandi* for structuring a problem is the workshop, while Kangas et al. (2008) highlighted that surveys and public hearings are the most commonly used tools for identifying stakeholders' preferences in respect to a certain problem. In our study we opted for the survey approach which consists of decomposing the decision problem into criteria and sub-criteria based on a direct subjective method of estimating the preference weights (Kangas et al., 2008).

Starting from a Delphi analysis conducted in Austria regarding the evaluation of technical, silvicultural and socio-economic effects of forest infrastructure (Steinmüller and Stampfer, 2004) we defined four main criteria for the assessment of forest road options, grounded on the sustainability pillars: *(A) Forest management, (B) Costs, (C) Environment protection* and *(D) Risks and social factors*. These criteria were decomposed into fifteen sub-criteria, which were allocated measurable indicators and objective functions (Table 1). This procedure was conducted by five experts in forest engineering from Austria and Romania. The sub-criteria are independent within the same criterion. This structure allows an effective evaluation and comparison of the forest road options with respect to each criterion and sub-criterion using MAUT or other MCDM tool (Kangas et al., 2008). Although the analytic hierarchy process (AHP) proved its utility in dealing with forest road problems (Coulter et al., 2006), this is a complex tool requiring expert judgments based on pairwise comparisons, which in turn requires a good understanding of the AHP tool by the end users. Thus, since in our study we conducted an online survey, MAUT was preferred for its simplicity in use and versatility (i.e. MAUT allows sensitivity analysis regarding the influence of stakeholder preferences in the final utility score of the alternatives).

The indicators were so defined that they could be easily measured or calculated using GIS tools, being directly or indirectly dependent on different measurable variables. The stakeholders were asked to assign their relative preference weights only to criteria and sub-criteria, but not to the indicators which were used to describe each sub-criterion. The preference weights thus obtained can be used for calculating the overall performance of forest road options by multiplying the standardized score of each evaluation sub-criterion by the corresponding weight of the criterion which belongs and then summing across the attributes (Ananda and Herath, 2009; Kangas et al., 2008). One example in this respect is the linear additive utility function that we used in our study (Eq. 1).

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

Table 1. Criteria and sub-criteria evaluated within the survey

Criterion	*Sub-criterion*	*Indicator*	*Objective function*
A. Forest management	A1. Independence of neighbours	1= the road passes through only one property; 0= the road passes over several properties	max
	A2. Accessibility for execution of forest operations	% of areas in the 300 m corridor from forest roads	max
	A3. Accessibility for game management	Maximum distance from the road to the furthest point in the project area	min
	A4. Loss of productive land (road bed clearance)	Road length X opening width	min
B. Costs	B1. Road construction costs	Annuity of investments in forest roads construction	min
	B2. Road maintenance costs	Total yearly maintenance costs	min
	B3. Harvesting costs	Total yearly harvesting costs	min
C. Environment protection	C1. Protection of ecologically valuable areas	Total cumulated distance to ecological valuable areas	max
	C2. CO_2 emissions	CO_2 Emissions from harvesting machineries and timber trucks	min
	C3. Visual disturbance of landscape	Number of curves, serpentines, intersections	min
D. Risks and social factors	D1. Accidents in forest operations	Time needed for first aid teams to arrive at accident location	min
	D2. Risk of soil erosion and landslides	Risk factor calculated based on models of soil erosions	min
	D3. Accessibility for touristic, local and cultural purpose	Cumulated distance to the points of interest	min
	D4. Accessibility in case of forest fires	Share of areas in the 200 m corridor from forest roads	max
	D5. Accessibility in case of wind-throws	Share of areas in the 300 m corridor from forest roads	max

where: U_i - the overall utility of alternative i; c_{ji} - performance of alternative i with respect to criterion j (normalized value); a_j - importance weight (preference) of criterion j.

Enache et al. (2013) showed how the additive utility function can be used in benchmarking forest road options, while Kühmaier and Stampfer (2010) showed how this can be done in the multiple criteria assessment of harvesting systems scenarios using GIS.

2.2. Survey elaboration

An online form containing the evaluation criteria and sub-criteria of the forest roads was prepared and a survey was conducted in Romania in November 2012. A cover letter describing the aim and the timeframe of the survey, together with the necessary instructions for filling out the forms were sent via e-mail to 103 stakeholders, such as: central authorities from the forestry sector, environmental agencies, watershed management agencies, universities and forest research institutes, forest owners, forest administrations, forest contractors and NGOs (Table 2). The stakeholder groups were selected based on the experience of three Romanian forest engineering experts regarding the most relevant stakeholders that are affected by and should therefore be involved in the decision making of forest road planning and engineering. The timeframe set for the participation at the survey was between 1st November 2012 and 20th November 2012. A reminder was sent to the stakeholders in the middle of this interval.

The survey form contained seven structured questions. The participants were first requested to choose their field of expertise (Table 2). Then, they were asked to express their preference weight according to the importance they assign to each criterion and sub-criterion based on a relative utility scale from 0% to 100% (Kangas et al., 2008). The following questions were formulated:

1. Which is the relative importance (weight) you assign to each of the following criteria used in the evaluation of forest road variants: (A) Forest management, (B) Costs, (C) Environment protection, (D) Risks and social factors?

2. Which is the relative importance (weight) you assign to each of the following sub-criteria in the assessment of forest road variants, (see Table 1):

a. Forest management: A1, A2, A3 and A4?

b. Costs: B1, B2 and B3?

c. Environment protection: C1, C2 and C3?

d. Risks and social factors: D1, D2, D3, D4 and D5?

3. Do you consider that other criteria and/or sub-criteria should be included in the evaluation of forest road variants without overburdening the decision making process? If so, please mention what these should be.

According to the multiple attribute utility theory, in order to reduce the bias of the utility of a criterion by increasing or decreasing its weight, the sum of the preference weights of a criterion must be 1 (Kangas et al., 2008). In our study, this means that both the sum of the preference weights assigned to criteria as well as the sum of preference weights assigned to the sub-criteria of a specific criterion had to sum to 100% (e.g. criteria weights A+B+C+D=100%; sub-criteria weights A1+A2+A3+A4=100%). No confidential data was requested from the participants.

2.3. Statistical analysis of stakeholder groups preferences

The responses of stakeholder groups have been analysed in terms of statistical significance and regarding the different behaviour between and within stakeholders' groups. In order to reduce the bias of too few or too many respondents from the same field of expertise, for calculating the mean preference weights (MPW) of the evaluation criteria and sub-criteria in Table 3, each group of expertise was considered to have equal importance.

Table 2. Field of stakeholders' expertise and participation rate

Code	*Field of expertise or role played by the stakeholder in the forestry sector*	*Number of sent forms*	*Number of respondents*	*Rate or response (%)*
E1	Forest owners	7	1	14%
E2	Forest administrations	8	3	38%
E3	Research and development (R&D) in forestry (e.g. silviculture, ecology, forest protection)	12	1	8%
E4	R&D in forest engineering (e.g. harvesting operations, forest roads)	14	7	50%
E5	Forest contractors (e.g. harvesting companies)	4	2	50%
E6	Forest roads contractors (e.g. designer, constructor)	3	1	33%
E7	Transport contractors (e.g. timber or gravel transporter)	3	0	0%
E8	Environmental protection agencies	23	9	39%
E9	Non-governmental organization (NGO)	3	1	33%
E10	Watershed management agencies	20	0	0%
E11	Wildlife management	3	0	0%
E12	Other field (i.e. tourism)	3	2	67%
TOTAL		**103**	**27**	**26%**

The weighted preference weight (WP) of each sub-criterion was calculated by multiplying the MPW with the corresponding un-weight preference (UWP) of the sub-criterion.

Responses given by the stakeholder groups were combined and analysed in cross-tabulations, in order to evaluate if there was any significant variation between groups. The analyses were performed in PASW® Statistics 18 SPSS Inc. *Levene's test* was performed for identifying the type of variance and the analysis of variance (ANOVA) was performed for determining whether all group means were the same (Hilton and Armstrong, 2006). For non-homogenous variance between the groups Welch's *t* test was performed. In the case of significant differences between the means, post-hoc ANOVA tests were performed in order to identify which stakeholder groups behave differently to the others. Hilton and Armstrong (2006) highlighted that different post-hoc tests may lead to the same results, although each test addresses the problems in its unique way. The expertise groups were not equally represented in the validated survey forms (see Table 2). Hence, stakeholder groups E1 (Forest owners), E3 (R&D in forestry), E6 (Forest road contractors) and E9 (NGOs) were excluded from the post-hoc analysis of the statistical significance, for having only one respondent each. However, these groups were included in ANOVA and in the graphical analysis. For homogenous variances, *Duncan's tests* were conducted. Despite the fact the *Duncan's tests* are more sensitive to type 1 error (i.e. incorrect rejection of the true null hypothesis), being given the small sample size of the groups, they were considered preferable in front of *Bonferroni tests* or *Scheffé's tests* which are more conservative and recommended for a larger number of group respondents (Backhaus et al., 2011; Bühl, 2010; Hilton and Armstrong, 2006). For non-homogenous variance the *Tamhane-T2 test* were performed.

For all performed statistical analysis, the significance level was set to 5%. All results interpretations were subject to variable standard errors of the expressed preferences between 6% and 18% (average of 10%±3%). Graphical interpretation of the expressed preferences by stakeholder groups was also performed.

3. Results

3.1. Participation rate

Out of the 103 surveys which were sent by e-mail, 100% were successfully delivered to the recipients, a total of 30 surveys were completed and sent back in the established timeframe and 27 survey forms were validated. The invalid survey forms were either incomplete or the data introduced was inconsistent (i.e. sum of the weights assigned to criteria or sub-criteria of specific criterion was different than 100%). The respondents within group E12 were both from the field of tourism. Expertise groups E7 (Transport contractors), E10 (Watershed management agencies) and E11 (Wildlife management) had no responses at all. The response rate varied between the stakeholder groups from 0% to 67% and the overall response rate was about 26% (see Table 2).

3.2. Empiric evaluation of stakeholder groups preferences

3.2.1. Opinions regarding criteria

The overall importance assigned by the stakeholder groups to each defined criterion and sub-criterion for the evaluation of forest road options is presented in Table 3.

The variation of the mean preference weights expressed by stakeholder groups for criteria is presented in Fig. 1, *Forest management* criterion (MPW 38%, see Table 3), which refers to the role of forest roads in fulfilling forest management objectives, is considered the most important criterion for the evaluation of forest road variants. Weights given to *Costs* (26%) and *Environment protection* (24%) criteria were almost equally placed second on the level of importance by the stakeholders, while *Risk and social factors (12%)* criterion was considered the least significant for the evaluation of forest road options.

3.2.2. Opinions regarding sub-criteria

In respect to the importance of the sub-criteria in the evaluation of the forest road options, Fig. 2, Fig. 3, Fig. 4 and Fig. 5 show there is a noticeable variability among stakeholder groups' preferences, depending on their field of expertise. In general, the surveyed groups consider the sub-criteria *A2 - accessibility for execution of forest operations, C1 - protection of ecologically important areas* and *B1 – road construction costs* as the most relevant ones, with weighted preference values of 20%, 14% and 11%, respectively (Table 3). On the contrary, sub-criteria *D3 - accessibility for touristic, local and cultural purpose* (1%) and *D5 - accessibility in case of wind-throws* (2%) were assigned the lowest preference weight. It seems stakeholder groups have a common opinion that *A2 - accessibility for execution of forest operations* is the most important *Forest management* sub-criterion (Fig. 2), while the preference weights expressed for the *Costs* sub-criteria appear to be more homogenous (Fig. 2).

In addition, Table 3 shows the surveyed groups of expertise consider *B2 – road maintenance costs* of equal importance to *B3 - harvesting costs*, while *B1 – road construction costs* is the most important cost sub-criterion when evaluating forest road options. A more clear variability in stakeholder groups perception was visible in case of *Environment protection* sub-criteria (Fig. 4), the outlined general opinion being that *C1 - protection of ecologically valuable areas* is the most important environmental sub-criterion, while sub-criteria *C3 – visual disturbance of landscape* and *C2 - CO_2 emissions* are seen as less important environmental factors (Table 3).

Table 3. Overall stakeholder groups' preferences for criteria and sub-criteria

Criteria	*MPW* (%)*	*SUB-CRITERIA* CODE	*UWP**	*WP**
A. Forest management	**38%** (±14%)	A.1. Independence of neighbours	21%	**8%**
		A.2. Accessibility for execution of forest operations	54%	**20%**
		A.3. Accessibility for game management	12%	**4%**
		A.4. Loss of productive land	13%	**5%**
B. Costs	**26%** (±9%)	B.1.Road construction costs	43%	**11%**
		B.2.Road maintenance costs	27%	**7%**
		B.3.Harvesting costs	30%	**8%**
C. Environment protection	**24%** (±13%)	C.1.Protection of ecologically valuable areas	57%	**14%**
		C.2.CO_2 emissions	19%	**4%**
		C.3.Visual disturbance of landscape	24%	**6%**
D. Risk and social factors	**12%** (±6%)	D.1.Accidents in forest operations	22%	**3%**
		D.2.Risk of soil erosion and landslides	21%	**3%**
		D.3.Accesibility for touristic, local and cultural purpose	11%	**1%**
		D.4.Accesibility in case of forest fires	28%	**3%**
		D.5.Accesibility in case of wind-throws	18%	**2%**
TOTAL	**100%**			**100%**

**Note: MPW – mean preference weight; UWP – un-weight preference; WP – weighted preference*

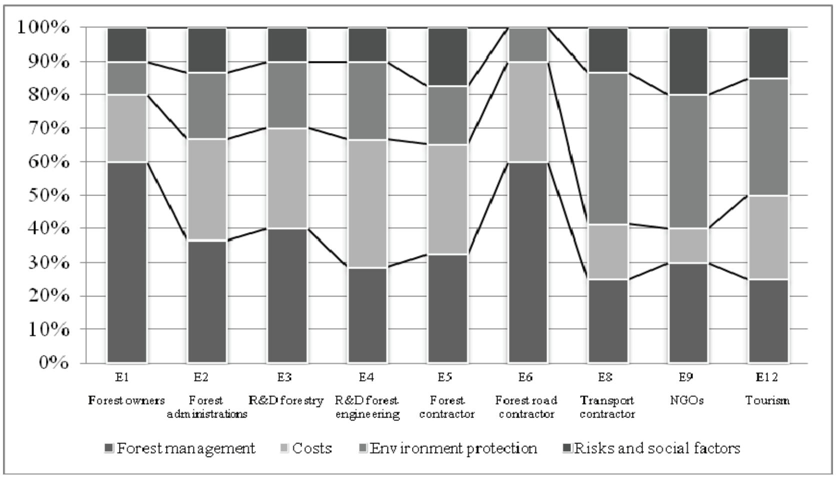


Fig. 1. Mean preference weights for criteria, by stakeholder group (E1-E12)

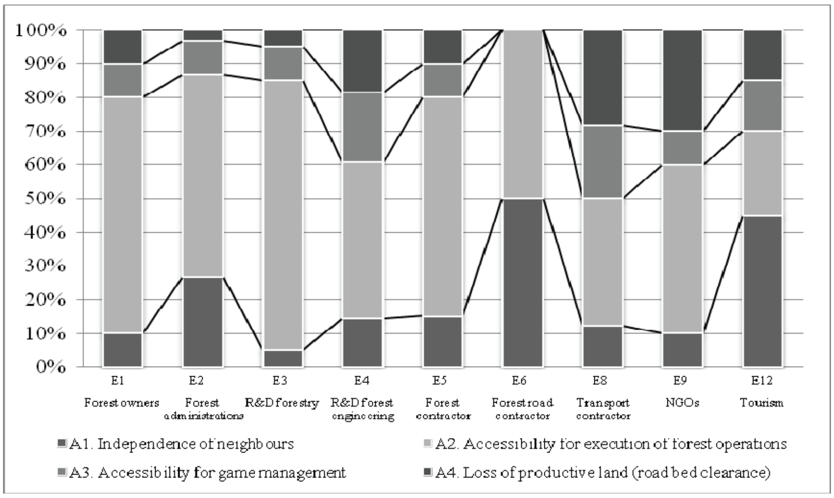


Fig. 2. Mean preference weights for *Forest management* sub-criteria

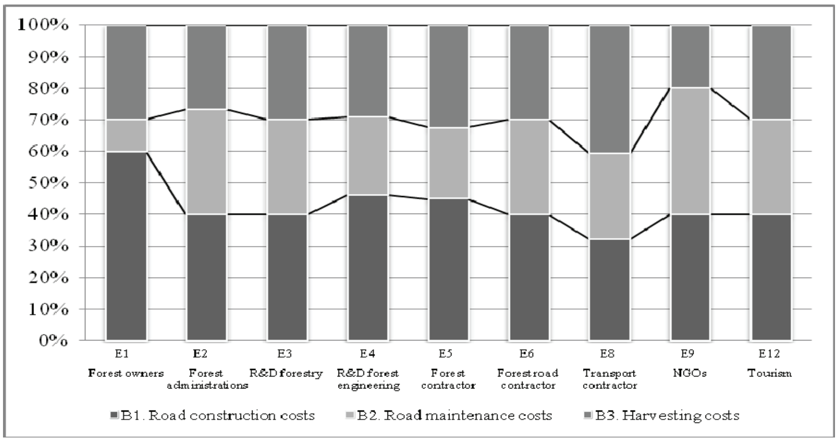


Fig. 3. Mean preference weights for *Costs* sub-criteria

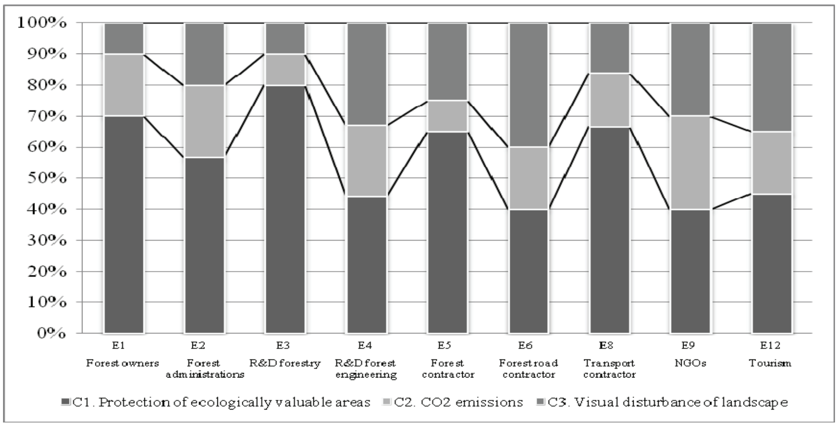


Fig. 4. Mean preference weights for *Environment protection* sub-criteria

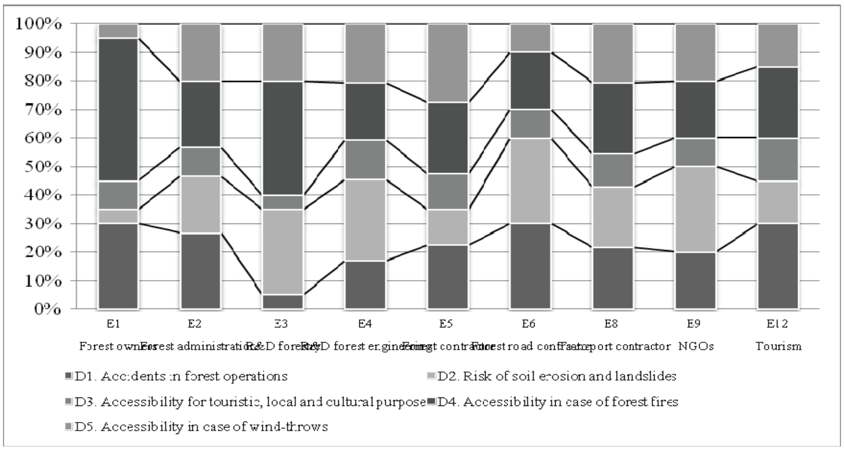


Fig. 5. Mean preference weights for *Risk and social Factors* sub-criteria

Regarding *Risk and social factors* sub-criteria, Fig. 5 shows a wide variability of stakeholders' preferences and a general impression that sub-criterion *D3 - accessibility for touristic, local and cultural purpose* is the least important sub-criterion. Although the weighted preference value of the sub-criterion *D4 - accessibility in case of forest fires* is similar to those of sub-criteria D1 - *accidents in forest operations* and *D2 – Risk of soil erosion and landslides*, the un-weight preferences show a higher importance assigned to accessibility in case of forest fires (Table 3).

Six stakeholders belonging to five expertise groups provided feedback to the third question formulated in the survey (Table 4). Respondents from the groups with expertise in forestry considered timber harvesting technology and extraction distance should be added to the evaluation sub-criteria, while the respondents from the environmental protection agencies additionally proposed the disturbance of protected areas and the impact of forest roads on biodiversity.

Table 4. Stakeholder proposals of other evaluation sub-criteria, by group of expertise

Expertise group	*Proposed sub-criteria*
E2 (forest administration)	Timber harvesting technology
E4 (R&D in forest engineering)	Possibility of using environmentally friendly timber harvesting technology
E5 (forest contractor)	Extraction distance; timber harvesting technology
E6 (forest road contractor)	Extraction distance
E8 (environment protection agency)	Necessity of forest roads and their impact on environment and biodiversity
E8 (environment protection agency)	Disturbance of protected areas

Table 5. Duncan [a, b] tests of stakeholders' preferences for the *Environment Protection* criterion

Expert group	*N^o^.*	*Subset*		
		1	*2*	*3*
E2 (forest administration)	3	.2000		
E5 (forest contractor)	2	.2000		
E4 (R&D in forest engineering)	7	.2571	.2571	
E12 (tourism)	2		.3500	.3500
E8 (environment protection agencies)	9			.4556
Sig.		.335	.106	.069

Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean. Square (Error) = .005. a. Uses Harmonic Mean Sample Size = 3.150. b. Alpha = .05. Calculation limited to stakeholder groups with two or more valid responses.

3.3. Statistical interpretation of stakeholder groups' preferences

Referring to the stakeholder groups opinions on evaluation criteria, one-way ANOVA revealed significant difference between stakeholder groups in respect to the *Environment protection* criterion (F=10.196; df=8, 18; p=0.000; α=0.05), while no differences were noticed for other criteria.

Duncan's multiple range tests indicated that the preferences expressed for *Environment protection* criterion tend to homogenously cluster by expertise groups in three subsets (Table 5). The preference weights assigned to this criterion by the environment protection agencies (group E8; mean weight 46%) and by the tourism stakeholders (group E12; 35%) showed a similar pattern, being higher than those assigned by forest contractors (group E5; 18%), forest administrations (group E2; mean weight 20%) and R&D in forest engineering (group E4; 24%), respectively.

In what concerns stakeholder groups' behaviour regarding the weighting of all 15 sub-criteria, Duncan's tests showed significant differences between the groups only for the sub-criteria within the *Forest Management* criterion. In this respect, Table 6 reveals a tendency of homogenous clustering of stakeholder groups opinions in two subsets, indicating that groups E4 (R&D in forest engineering), E5 (Forest contractors) and E8 (Environment protection agencies) assign a lower importance to sub-criterion *A1 - independency of neighbours* than groups E2 (Forest administrations) and E12 (Tourism). The same tests reported significantly lower preference weights of the group E12 (tourism stakeholders) than all other groups in respect to the sub-criterion *A2 - accessibility for execution of forest operations,* thus showing the lack of interest or the lack of awareness of tourism stakeholders in respect to the important role of forest roads in performing forest operations. Regarding the sub-criterion *A4 - loss of productive land*, despite the tendency of clustering in two homogenous clusters, there is a clear difference between the importance weights assigned by the environment protection agencies (group E8) on one hand, and those of forest administrations (group E2) and forest contractors (group E5), on the other hand (Table 6).

The within group variability of those stakeholders groups with more than one respondent was not thoroughly analysed in this study. However, the standard deviation (SD) of the preference values expressed for criteria and sub-criteria by individuals within such groups was determined. A certain degree of variability was noted within groups E2 (forest administrations), E4 (forest road contractors) and E8 (environmental agencies), while more homogeneity was noted within groups E5 (forest contractors) and E12 (tourism). However, it was noted that inside the same expertize group it can be both consensus regarding certain criteria or sub-criteria and divergent opinions regarding other sub-criteria, in some extent. For example, individuals from group E2 (forest administrations) shared similar opinions in respect of importance of criteria (SD= 0% to 6%), but showed more divergent opinions regarding sub-criteria like *accessibility for execution of forest operations* (SD= 30%) or *protection of ecologically important areas* (SD= 31%).

Individuals within group E8 (environmental agencies) showed some variability regarding *harvesting costs* (SD= 19%) and *accidents in forest operations* (SD= 17%) sub-criteria, while forest road contractors (group E4) for *accessibility for execution of forest operations* (SD= 17%) and *loss of productive land* (SD= 17%) sub-criteria.

Table 6. Duncan [a, b, c] tests for *Forest management* sub-criteria

Sub-criterion	***Expert groups***	***N***	***Subset***	
			1	***2***
A1 - Independency of neighbours (Duncan [a,c])	E8	9	0.1222	
	E5	2	0.1500	
	E4	7	0.1571	
	E2	3	0.2667	0.2667
	E12	2		0.4500
	Sig.		0.248	0.116
The error term is Mean Square (Error) = 0.019.				
A2 - Accessibility for execution of forest operations (Duncan [a,b,c])	E12	2	0.2500	
	E8	9	0.3778	0.3778
	E4	7	0.4714	0.4714
	E2	3		0.6000
	E5	2		0.6500
	Sig.		0.131	0.074
The error term is Mean Square (Error) = 0.028.				
A4 - Loss of productive land (Duncan [a,c])	E2	3	0.0333	
	E5	2	0.1000	0.1000
	E12	2	0.1500	0.1500
	E4	7	0.2000	0.2000
	E8	9		0.2889
	Sig.		0.166	0.119
The error term is Mean Square (Error) = 0.018.				

Means for groups in homogeneous subsets are displayed. Based on observed means. a. Uses Harmonic Mean Sample Size = 3.150. b. The group sizes are unequal. The harmonic mean of the group sizes is used. c. Alpha = 0.05. Calculation limited to stakeholder groups with two or more valid responses.

Nevertheless, no generalization can be made in respect of the degree of variability of responses within the stakeholder groups, because of the low number of respondents within each group. Maybe only groups E8 and E4, with nine and seven respondents respectively, could show a more generalized pattern of within group variability.

4. Discussions

The response rate at the survey conducted in this study was 26%. Surveys conducted in the forestry sectors of other countries reported higher response rates (Esseks and Moulton, 2000 – 71% response rate; Moulton and Esseks, 2001, – 72%; Munsell and Germain, 2004, - 42%; Nadeau et al., 2007 – 62%), whereas Rottensteiner and Stampfer (2011) reported response rates between 12% and 21% in a survey regarding the training of forestry technicians conducted in Austria, Germany and Switzerland. Some of the stakeholder groups invited to participate in our survey (i.e. watershed management agencies, wildlife management) expressed no feedback. This was similar to what Austroprojekt (2008) reported in a survey conducted in the Romanian forestry sector: a response rate of 33% after numerous reminders sent to the stakeholders and with certain groups not giving any feedback in the end. However, in a survey focused on identifying current challenges of forest management which targeted all managers of private forest districts in Romania, Abrudan (2012) reported a final response rate of 67% after the questionnaire was introduced in a formal meeting of the Association of Private Forest Administrators. Although a non-response analysis was conducted among some of the respondent stakeholders in this study (i.e. ten Romanian forest and university experts), which were asked to fill in post-survey feedback forms in order to find out the reason for the low response rate, no feedback was received in this respect. It seems the response rates in surveys depend on many factors, from the social, economic and cultural framework in which they are developed, up to the survey method (by mail, by workshop, by direct interview) or the field of expertise, level of survey's subject matter understanding and motivation of the participating stakeholders. Thus, perhaps a workshop or a public hearing (Mingers and Rosenhead, 2004; Kangas et al., 2008) where the survey is formally introduced to targeted stakeholders (Abrudan, 2012) could help in better framing a survey's relevance in the decision making process, which could lead to a higher response rate.

In what concerns the opinions regarding evaluation criteria, it was confirmed that the interviewed stakeholder groups consider *Forest management* is the most important criterion for the evaluation of forest roads. Whilst former practices in Romania approached development of forest infrastructure based more on technical-economical assessments, an unexpected positive result was the surveyed groups have shown an increased level of awareness regarding the environmental footprint of the forest roads, the *Cost* and *Environment protection* criteria being assigned almost equal importance. This fact shows forest stakeholders have become more concerned and open to dialogue on issues regarding environment and nature conservation, which might be a result of the EU and national policies implemented in the forest sector in the last decade (Abrudan et al., 2009).

Regarding stakeholder groups opinions on the role and importance of sub-criteria in the evaluation of forest road options, despite the fact there were different perceptions between the groups in respect of the importance assigned to the *Environment protection* criterion in evaluating forest road options, no significant differences between the stakeholder groups preferences assigned to *Environment protection* sub-criteria were noticed. This means the surveyed stakeholders in our study understand and are aware of the environmental footprint of forest roads, but the level of concern on this topic differs between stakeholder groups. For example, tourism stakeholders and environmental agencies showed more sensitivity to environmental issues (i.e. loss of productive land, protection of ecological valuable areas) than stakeholders with forestry backgrounds and interests. Thus involving all relevant stakeholders in forest road planning could foster the adaptation of the operational plans to the concept of multiple-use forestry in order to meet the environmental and social requirements.

In the framework of the current European forest policies (EU, 2013; EU, 2010) which emphasize the importance of forests as carbon sinks and the need for reducing GHG emissions in forest operations, and in line with Kilpeläinen et al. (2011) which showed CO_2 emissions are an important factor in the assessment of the environmental impact of multiple use forestry regimes, an unexpected fact in this study was that stakeholders considered the *CO_2 emissions* (sub-criterion C2) less important than the *visual disturbance of the landscape* (sub-criterion C3). However, the findings of Abrudan (2012) showed similar reduced interest and concern of Romanian forest managers regarding carbon storage issue.

Regarding *Risk and social factors* sub-criteria, first we have to stress that about 28% of Romanian forests are exposed to high and very high risk of wind-throws, while 18% are exposed to medium risk (Dinca et al., 2008). In this context, it is not clear why the stakeholders have assigned such a low importance to sub-criterion *D5 - accessibility in case of wind-throws*, since the negative ecological and economic impact of wind-throws and the necessity of a system for risk management against wind-throws in Romanian mountain forests are already acknowledged (Popa, 2005). Furthermore, another unexpected response of stakeholders was that, although the risk of forest fires in Romania is considerably lower than in other European countries, only 9% of the national forest land being exposed to a medium or high risk of fire (Adam, 2007), the respondents considered sub-criterion *D4 – accessibility in case of forest fires* more important than the accessibility in case of wind-throws.

As regards to the sub-criterion *D3 – accessibility for tourism, local and cultural purpose*, participant stakeholders in this study assigned a low importance to this sub-criterion in the decision making process of forest roads engineering, although the multi-purpose role of forests and forest roads and their positive impact on tourism are well recognized (Abrudan et al., 2009). This is in some extent surprising, since significant financial resources have been allocated within the last decade for infrastructure development in forested areas (MARD, 2013) and that the multi-functional role of forests is well-recognized by the national Romanian forest strategy (MENVF, 2011). In comparison, in a survey regarding the importance, use and role of forests in a Canadian province, Nadeau et al. (2007) reported that two thirds of the respondents agreed forests should be managed to meet as many human needs as possible.

The findings of this study can be used in guiding decision-making in forest road network planning through stakeholder preferences, but they can also be used to identify those areas of the planning process which do not appear relevant to stakeholders and thus require attention. One such example is the low priority assigned by stakeholders to social factors. The normative regarding forest roads designing in Romania (MENVF, 2012) includes an entire chapter with recommendations for labor protection and improved ergonomics, which should be duly considered during planning process. Reducing the number of accidents in forest operations, better accessibility for touristic purpose or in case of accidents, and minimizing the risk of soil erosion, landslides and torrential flows which could severely affect the downstream communities, should also be well regarded when planning forest road networks. These aspects should represent a matter of future focus in the light of the desired increase of corporate social responsibility in the Romanian forestry sector.

The feedback stakeholders gave regarding possible additional evaluation sub-criteria (i.e. question number three, Table 4) revealed that harvesting technology and extraction distance are important factors for the evaluation of forest road options in the viewpoint of foresters. We concur with these proposals, since harvesting technology and extraction distance influence the density and the location of the forest road networks. In this respect, we underline that while harvesting technology was not included in our listed sub-criteria, the extraction distance was indirectly linked with sub-criteria A2 (accessibility for execution of forest operations) and B3 (harvesting costs). However, it seems this was not very clear to the stakeholders. This remark also applies for the environment protection sub-criteria, since there is only a matter of sensitivity between the proposals of additional sub-criteria made by the stakeholders with environmental expertise and the environmental sub-criteria defined in our study. Hence, we consider a face to face stakeholder interaction (i.e. workshop, conference) would be beneficial for better describing and more clearly defining evaluation criteria and sub-criteria. In addition, the workshop approach, especially in case of projects with local importance (i.e. forest road planning, selection of timber harvesting systems) and low number of stakeholders, could allow the utilization of other more complex MCDM methods (such as AHP or fuzzy AHP) in order to deal with the uncertainty of subjective evaluation of the stakeholder preferences on decision criteria and indicators.

This study showed how the assessment of road options can be structured in criteria and sub-criteria and how stakeholders can independently prioritize their preferences regarding evaluation criteria and sub-criteria of the forest roads. This weighting process is required in the application of MAUT in the benchmarking of decision alternatives. Kangas et al. (2008) reported that questioning the decision makers regarding the importance of evaluation criteria and sub-criteria is useful for the decision support. Our study also revealed how much stakeholder groups preferences can vary, depending on their expertise field and knowledge about forestry. Hence, we consider that in practice, the methodology presented in our study for defining and weighting criteria and sub-criteria could and should be used for benchmarking forest road options prior to technical designing. This should be done within the framework of a workshop or round table discussion, by involving all relevant local stakeholders, thus giving a strong CSR dimension to the process of forest road network planning, in particular, and to forest management, in general.

The weighted stakeholders' preferences (Table 3) for evaluation sub-criteria are useful in the decision making process of benchmarking decision alternatives and selecting the most suitable forest road option. An example in this respect was presented by Enache et al. (2013) which used the weighted preferences of the evaluation sub-criteria reported in this study to calculate the total utility scores of four forest road scenarios using MAUT. The authors showed through sensitivity analysis how important are the stakeholders' preference weights in the final utility score of the decision alternatives. Using this participatory approach from the early stages of forest road planning could lead to time savings in obtaining the necessary permits and authorizations from different bodies and could lower the risk of the project being delayed or rejected, because the authorities are better documented and informed on the project issues. An alternative way of estimating the utility function of decision alternatives (e.g. forest road options) was proposed by Kangas et al. (2008) which suggested that direct holistic evaluation of these alternatives could also be useful. However, in the context of a complex decision problem which involves conflicting interests of multiple stakeholders, such as the forest road network planning, it is more appropriate to first clearly define and structure the decision problem into criteria and sub-criteria and then to evaluate the performance of the decision alternatives based on preference weights assigned to the components of this structure, as it was presented above.

5. Conclusions

This study about stakeholder groups' opinions on evaluation criteria and sub-criteria of forest roads revealed a consensus between groups in respect to *Forest management, Costs* and *Risks and social factors* criteria and more divergent opinions regarding *Environment protection* criterion. The study showed stakeholder preferences can be used in guiding decision-making in forest management related problems. Though, it should be noted that the online (e-mail) surveys may not be a preferred method for measuring stakeholder preferences due to several reasons like: possible low response rate, reduced level of flexibility in describing and discussing the criteria and indicators, and lack of face to face interaction between stakeholders. Thus, it is recommended the methodology presented in this study to be applied in practice in the form of workshops, decision conferencing or round table discussions, involving all relevant stakeholders. In this way decision making in forest management could benefit a participatory and transparent process, increasing the corporate social responsibility and the implementation of SFM principles in the forest sector.

Acknowledgements

This paper was supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), ID76945 financed from the European Social Fund and by the Romanian Government. We would like to thank the participants at this survey for their input and the four anonymous reviewers for their valuable comments and suggestions.

References

Abrudan I.V., Marinescu V., Ionescu O., Ioras F., Horodnic S.A., Sestras R., (2009), Developments in the Romanian forestry and its linkages with other sectors, *Notulae Botanicae Horti Agrobotanici Cluj-Napoca,* **37**, 14-21.

Abrudan I.V., (2012), A decade of non-state administration of forests in Romania: achievements and challenges, *International Forestry Review*, **14**, 275-284.

Adam I., (2007), A method of assessing the risk of forest fires in Romania (in Romanian), *Annals of Forest Research – Journal of Forestry and Environmental Sciences*, **50**, 261-271.

Ananda J., Herath G., (2009), A critical review of multi-criteria decision making methods with special reference to forest management and planning, *Ecological Economics*, **68**, 2535-2548.

Austroprojekt, (2008), Forestry and Forest Industry in Romania – Wood Supply Sector Study – Final Report to the Ministry of Agriculture and Rural Development, 169.

Backhaus K., Erichson B., Plinke W., Weiber R., (2011), *Multivariate Analyse Methods – An Application Oriented Implementation,* Thirteen extended edition (in German), Springer-Verlag Berlin Heidelberg.

Bühl A., (2010), *PASW 18. Introduction to modern data analysis – Twelfth updated edition* (in German), Pearson Studium – Pearson Education Deutschland GmbH, 1004.

Costa R., Menichini T., (2013), A multidimensional approach for CSR assessment: the importance of the stakeholder perception, *Expert Systems with Applications*, **40**, 150-161.

Coulter E.D., Sessions J., Wing M.G. (2006), Scheduling forest road maintenance using the analytic hierarchy process and heuristics, *Silva Fennica*, **40**, 143-160

Diaz-Balteiro L., Romero C., (2008), Making forestry decisions with multiple criteria: A review and an assessment, *Forest Ecology and Management*, **255**, 3222-3241.

Dinca L., Cioloca N., Bujila M., (2008), Risk map of wind-throws for Romanian forests, On line at: http://www.icasbv.ro/?page_id=572.

Enache A., Kühmaier M., Stampfer K., Ciobanu V.D., (2013), An integrative decision support tool for assessing forest roads options in a mountainous region in Romania, *Croatian Journal of Forest Engineering*, **34**, 43-60.

Enescu A.H., (2011), *Research about the usefulness and economic efficiency of forest transport network development, in the mountain area, with summary arranged roads and their characteristics* (in Romanian), PhD Thesis, Transilvania University of Brasov, Romania.

Esseks J.D, Moulton R.J., (2000), *Evaluating the Forest Stewardship Program through a National Survey of Participants*, Proceedings of the Southern Forest Economics Workers 2000: Hardwoods - an underdeveloped resource?, Lexington, Kentucky, USA, March 26-28, 168-175.

European Commission (EC), (2013), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: *A new EU Forest Strategy*: *for forests and the forest based sector*. SWD(2013) 342 final. SWD(2013) 343 final.

European Union (EU), (2010) Green Paper on Forest Protection and Information in the EU: Preparing forests for climate change – COM(2010)66 final {SEC(2010)163 final}. European Commission, 23.

FAO, (2010), FAO Strategy for forests and forestry. On line at: http://www.fao.org/docrep/012/al043e/al043e00.pdf.

Ferrario P., Fumagalli N., Senes G., Toccolini A., (2014), Composite assessment of productive, protective and recreational functions in forest planning, *Environmental Engineering and Management Journal*, **13**, 1277-1290.

Forest Europe, (2011), Oslo Ministerial Decision: European Forests 2020, On line at: http://www.foresteurope.org/docs/ELM/2011/FORESTEUROPE_MinisterialConference_Oslo2011_EuropeanForests2020.pdf.

Glavas A., Godwin L.N., (2013), Is the perception of 'goodness' good enough? Exploring the relationship between perceived corporate social responsibility and employee organizational identification, *Journal of Business Ethics*, **114**, 15–27.

Gordon M., Lockwood M., Vanclay F., Hanson D., Schirmer J., (2012), Divergent stakeholder views of corporate social responsibility in the Australian forest plantation sector, *Journal of Environmental Management*, **113**, 390-398.

Green R., Luther J.E., Devillers R., Eddy B., (2010), An approach to GIS-based multiple criteria decision analysis that integrates exploration and evaluation phases: Case study in a forest-dominated landscape, *Forest Ecology and Management*, **260**, 2102-2114.

Hilton A., Armstrong R., (2006), Stat Note 6 – post hoc ANOVA tests, *Microbiologist*, **7**, 34-36.

Kangas A., Kangas J., (2005), Multiple criteria decision support in forest management - the approach, methods applied, and experiences gained, *Forest Ecology and Management*, **207**, 133-143.

Kangas A., Kangas J., Kurttila M., (2008), *Decision Support for Forest Management*, Springer Science+Business Media B.V., 223.

Kilpeläinen A., Alam A., Strandman H., Kellomäki S., (2011), Life cycle assessment tool for estimating net CO_2 exchange of forest production, *Global Change Biology Bioenergy*, **3**, 461-471.

Kühmaier M., Stampfer K., (2010), Development of a multi-attribute spatial decision support system in selecting timber harvesting systems, *Croatian Journal of Forest Engineering*, **31**, 75-88.

Lexer M.J., Vacik H., Palmetzhofer D., Oitzinger G., (2005), A decision support tool to improve forestry extensions service for small private forest owners in southern Austria, *Computers and Electronics in Agriculture*, **49**, 81-102.

MARD, (2013), Romanian National Program of Rural Development, Ministry of Agriculture and Rural Development, On line at: http://www.madr.ro/pages/page.php?self=03&sub=0302&art=030202&var=030202.

Mendoza A.G., Prabhu R., (2000), Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study, *Forest Ecology and Management*, **131**, 107–126.

MENVF, (2011), PSDFR - The policy and strategy for the development of Romanian forestry sector (2001-2010), Ministry of Environment and Forests On line at: http://www.mmediu.ro/paduri/politici_forestiere.htm.

MENVF, (2012), Normative PD-003-11 regarding forest roads designing, Ministry of Environment and Forests On line at: http://www.mmediu.ro/beta/wpcontent/uploads/2012/08/2012-08-07_paduri _normativproiectaredrumuriforest.pdf.

Matilainen A.M., (2013), Forest companies, corporate social responsibility, and company stakeholders in the Russian forest sector, *Forest Policy and Economics*, **31**, 44-49.

Mingers J., Rosenhead J., (2004), Problem structuring methods in action, *European Journal of Operational Research*, **152**, 530-554.

Moulton R.J., Esseks J.D., (2001), *Highlights of the National Evaluation of the Forest Stewardship Planning Program*, Proceedings of the Southern Forest Economics Workshop 2001 - Forest Law and Economics, Atlanta, Georgia, USA, March 27-28, 6 p.

Munsell J., Germain R., (2004), Forestry extension participation and written forest management plan use in New York City's water supply system, *Journal of Extension*, **42**, 2RIB7, 8.

Nadeau S., Beckley T.M., Huddart Kennedy E., McFarlane B.L., Wyatt S., (2007), Public Views on Forest

Management in New Brunswick: Report from a Provincial Survey – Information Report M-X-222E, Natural Resources Canada, Canadian Forest Service – Atlantic Forestry Centre, 77.

Popa I., (2005), Wind-throw – risk factor in mountainous forest ecosystems, (in Romanian), *Annals of Forest Research – Journal of Forestry and Environmental Sciences*, **48**, 171-195.

Rottensteiner C., Stampfer K., (2011), Forestry technicians NEW. A study commissioned by the agriculture and forestry Federal Apprentice and Technical Training Institution (in German), University of Natural Resources and Life Sciences – BOKU, Vienna, Austria, 61.

Sheppard S.R.J, Meitner M., (2005), Using multi-criteria analysis and visualization for sustainable forest management planning with stakeholder groups, *Forest Ecology and Management*, **207**, 171-187.

Steinmüller T., Stampfer K., (2004), ROADEVAL – Evaluation of the technical, silvicultural and socio-economic effects of the forest infrastructure development measures (German), Institute of Forest Engineering, University of Natural Resources and Life Sciences, Vienna, Austria, 32.

Widhalm H., Stampfer K., Ryan T., Abrudan I., Alexandru V., Bereziuc R., Ciobanu V., Ignea Gh., Derczeni R., (2005), *Best Practice Guidelines for Forest Roads in Romania*, In: *World Bank's Forest Development Project*, ÖBf Consulting and Transilvania University of Brasov, 40.

Wolfslehner B., Vacik H., (2008), Evaluating sustainable forest management strategies with the Analytic Network Process in a Pressure-State-Response framework, *Journal of Environmental Management*, **88**, 1-10.

Wolfslehner B., Bruchert F., Fischbach J., Rammer W., Becker G., Lindner M., Lexer M.J., (2011), Exploratory multiple-criteria analysis in sustainability impact assessment of forest-wood chains: the example of a regional case study in Baden-Wurttemberg, *European Journal of Forest Research*, **131**, 47-56.

World Bank, (2012), Functional analysis of the central public administration in Romania – II. Functional Analysis of the Sector Environment and Forests in Romania – Vol. 1 & 2. – Final Report SMIS Code: 37608 (in Romanian), Bucharest, Romania.

Machine Utilization Rates, Energy Requirements and Greenhouse Gas Emissions of Forest Road Construction and Maintenance in Romanian Mountain Forests

A. Enache and K. Stampfer

University of Natural Resources and Life Sciences, Vienna, Austria
Corresponding Authors: {adrian.enache; karl.stampfer}@boku.ac.at

Received 4 July 2014; Accepted 27 November 2014;
Publication 19 March 2015

Abstract

The FAO and EU forest strategies advocate the use of forest resources in ways which minimize the impact on the environment and climate. However, in forests with poor accessibility, the environmental footprint of forest operations is significant due to the long timber extraction distances. Thus, improving the environmental performance of forest operations requires a well-developed forest infrastructure, specifically the density and quality of roads. The aim of this paper was to assess the environmental footprint of forest roads in terms of embodied energy and greenhouse gas emissions due to construction and maintenance. In this respect, life cycle assessment approach was used to develop an input-output model for benchmarking two case study areas, considering real machine utilization rates, fuel consumption and labor requirements. The forest road life cycle was set to 30 years. Direct energy requirements derived from the fuel consumed by the machinery were considered. Construction and maintenance required energy inputs of 490.9 MJ m^{-1} and 580.4 MJ m^{-1}, respectively about 36.6 kg CO_{2eq} m^{-1} and 43.1 kg CO_{2eq} m^{-1} emission rates in the two case study areas, while occupying productive land with forest roads triggered a loss of 3.95 kg CO_{2eq} m^{-1} y^{-1} and 4.40 kg CO_{2eq} m^{-1} y^{-1} during the life cycle of the forest

Journal of Green Engineering, Vol. 4, 325–350.
doi: 10.13052/jge1904-4720.445

road. However, the CO_{2eq} loss due to road construction and maintenance is insignificant when compared to the CO_{2eq} stored in the growing stock of the opened forest area. Terrain characteristics showed a strong influence on the amount of fuel consumption, required energy input and GHG emissions, leading to higher environmental burden and higher road construction costs.

Keywords: Emissions, energy efficiency, forest, greenhouse gases, LCA, road construction, Romania.

1 Introduction

The EU 20-20-20 targets on climate change and energy sustainability envisage 20% reduction of greenhouse gas (GHG) emissions from 1990 levels and improving with 20% the energy efficiency by year 2020. Forests and their sustainable management play a major role in the reduction of GHG emissions level and in carbon storage in forest biomass (Kilpeläinen et al. 2011). The FAO and EU forest policy framework promote a holistic approach to the challenges of the entire forest value chain for adapting forests to climate change and for reducing the environmental footprint of forest operations within the framework of a low carbon economy. However, in forests with poor accessibility, the environmental footprint of forest operations is significant due to the long timber extraction distances.

Romanian forests cover 6.65 million ha (29% of the total land area; Abrudan et al. 2009) and have a poorly developed and unevenly distributed infrastructure (road density 6.5 m ha^{-1}; Olteanu 2008). Thus, skidding is the main method of timber extraction and the mean skid distance is about 1.8 km at national level (Popovici et al. 2003). Consequently, the environmental footprint of forest operations is high, while the productivity in timber harvesting and extraction is rather low (Borz et. al 2013; Enache et al. 2013). The average annual growth of Romanian forests is about 37 million m^3, the annual allowable cut (AAC) is 22.3 million m^3 and the average annual removal is about 17.0 million m^3 (World Bank 2012). About 65% of the forests are located in mountain ranges, 55% are state-owned forests and 45% non-state forests. The underdeveloped forest infrastructure makes sustainable forest management challenging, with significant pressure and environmental footprint on the accessible forests. However, the net forest growth in the last decades was positive, ranging between 15–17 million m^3 each year, triggering a consequent increase of carbon storage

(World Bank 2012). This means there is significant potential for increasing the sustainable wood mobilization, which requires a well-developed forest infrastructure.

Timber harvesting and road engineering have the most visible environmental impact in the forest sector. The life cycle assessment (LCA) is a suitable tool for approaching such challenges of the wood supply chain and for producing reliable indicators on the environmental performance of systems and processes in the forest sector (Heinimann 2012). Meister (1995) emphasized that the environmental balance of forest operations is based on mass flows and energy balance of inputs and outputs of a system. In addition, Richter (1995) stressed that defining the boundaries of a LCA system is difficult, highlighting that wood supports most of the negative burdens of the forest management activities, while other ecosystem services of the forest management with direct positive effects on people and the environment do not. The environmental performance of silviculture operations, timber harvesting and transport have been extensively addressed in the literature (Berg and Lindholm 2005; Johnson et al. 2005; Klvac and Skouppy 2009; Michelsen et al. 2008; Seppala et al. 1998; Klvac et al. 2012), while only few studies have included forest roads in the analyzed system boundaries (Berg and Karjalainen 2003; Bosner et al. 2012; Whittaker et al. 2011). American researchers focused more on the effects of forest roads on soil erosion, sedimentation and water quality (Coulter 2004; Mills, 2006; Loeffler et al. 2008), whilst European researchers focused on the embodied energy and GHG emissions of forest roads (Heinimann and Maeda-Inhaba 2003; Heinimann 2012; Whittaker et al. 2011). Since the environmental impact of roads relate to their construction, maintenance and use (Treloar et al. 2004), complete LCA of forest roads is difficult and time consuming, depending on the system boundaries and on the number of inputs in the process analysis. Hence, a hybrid process based and input-output based LCA approach is recommendable for estimating project specific environmental impacts of forest roads (Treloar et. al 2004; Sharrard 2007).

In this context, considering the current concerns on the environmental performance of forest management activities (Abrudan et al. 2009; Karjalainen et al. 2003; Michelsen et al. 2008; Olofsson et al., 2011), the aim of this paper was to quantify the embodied energy, the loss of productive land and the GHG emissions from forest roads construction and maintenance through a comparative assessment of two case study areas. In this respect, a hybrid LCA approach was used, referring to the functional unit of road.

2 Material and Methods

2.1 Pre-Set Standards

This study focused on the energy requirements and GHG emissions of forest roads due to construction and maintenance during their life cycle. In this respect, the following standards were established: real utilization rates of machinery and consumption rates of materials and labor; real transport distances for machinery and materials; AAC of the forest area assigned to the forest roads; the life cycle of the forest roads was set to 30 years. The CO_{2eq} emissions were determined for a complete cycle of the diesel combustion process based on a stoichiometric combustion model (Heinimann 2012), for a net calorific value of diesel engines of 42.76 MJ kg^{-1} (Stanescu 2012) and the diesel density of 0.835 kg m^{-3} (Berg and Karjalainen 2003). The loss of productive land due to road construction was quantified for an average annual growth of 6.0 m^3ha^{-1}. For timber transport, the truck and trailer system with loading capacity of 25 m^3 was considered.

2.2 Input-Output LCA Model and System Borders

The energy efficiency and the emissions of greenhouse gases are important elements in LCA which focuses on the global warming potential (GWP) of a system. A typical LCA consists of setting goals and objectives, inventory analysis, impact assessment and interpretation of results (Heinmann 2012), while an optimal hybrid LCA model for construction should include economics, on-site activities, equipment, transportation, water, energy and social equity related aspects (Sharrard 2007). The hybrid LCA is based on deriving an input-output (I-O) LCA model and then case-specific LCA data for the analyzed system which are substituted in the I-O model (Treloar et al. 2004).

Heinimann and Maeda-Inaba (2003) showed how the concepts of commodities and activities and the oriented graph theory can be used in investigating I-O flows in forest roads construction. Figure 1 shows the LCA model of forest roads developed in this study for investigating the input-output flows of the road construction and maintenance works. This model refers only to the life cycle inventory of the roads and allows identification of material, energy, labor and emission flows within the system. The model was applied for both road construction and maintenance works, referring to activities such as: preparatory works (i.e. transport of machinery and material to the site, road bed clearance); embankments execution, drainage system and pavement finishing; and maintenance works (i.e. pavement reshaping;

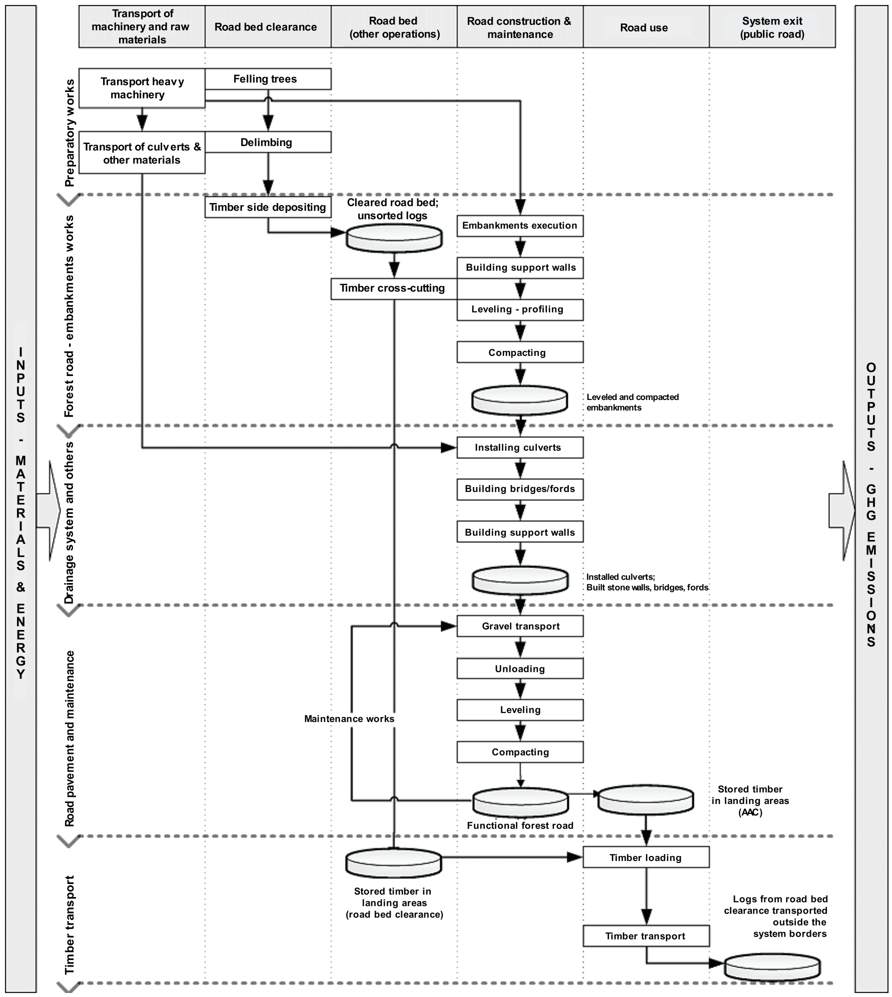


Figure 1 Life cycle I-O model for forest road construction and maintenance.

ditches reshaping). Direct energy requirements and greenhouse gas emissions were derived from the fuel consumed by machinery to carry out specific tasks (Whittaker et al. 2011), disregarding the energy and the emissions embodied in the machinery manufacture. The functional unit of the analyzed system set in this study was one meter of road.

Except for the timber cleared during the road construction, timber harvesting and transport were not included in analysis in this study. Accounting of the energy and emissions applied to timber harvesting and extraction with and without forest road will be approached in another study.

2.3 Building Technology Matrices

The quantification of the input and output flows for each phase of the LCA (Figure 1) were based on the technology matrices approach, using a system of linear equations which describe the flow of commodities into the system (Michelsen et al. 2008; Heinimann 2012), an example of which is presented in Table 1 for the phase of pavement works. The first row of the matrix shows the flow of labor necessary for a given process, taking into account the effective working time of a machine operator. The second row shows the fuel consumption rates of the machineries per productive system hour (PSH), which means the system includes both the machinery and the operator. The following rows were filled using the same reasoning. Thus, if a machine was not used in the system, all values in the row assigned to that machine were set to zero, except the diagonal value which was always set to value 1.

According to Heinimann (2012), assuming that each process can be scaled by a variable $x_{i(i=1\div n)}$, the system of equations can be solved for the vector $X\ (x_1, x_2, ..., x_n)$ if the total production of the system is known, that is vector Y, using the equations bellow.

Equation (1) $\mathsf{A} \cdot \mathsf{X} = \mathsf{Y}$
Equation (2) $\mathsf{X} = \mathsf{A}^{-1} \cdot \mathsf{Y}$

The economic performance of the systems was determined using a cost vector based on the machine hour costs computed with the FAO cost calculation scheme (Holzleitner, 2011), which was then multiplied with the performance vector X. Considering the direct correlation between the flow of commodities and their environmental footprint (Heinimann 2012), an environmental matrix similar to the technology matrix from the Table 1 was developed. This matrix was then multiplied with the performance vector X, and the environmental footprint vector of the analyzed system was thus determined. The technology matrix approach was used in benchmarking both forest road construction and maintenance works.

2.4 Case Study Areas (CSAs)

The research was conducted in *Lignum Forest Enterprise*, located in Bacau County (Romania), Eastern Carpathian Mountains (46°21′02"N, 26°20′42"E; Figure 2), in the surroundings of Accumulation Lake “*Valea Uzului*”

Table 1 Flow of commodities into the functional unit of road for pavement works

		Unit	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	
X1	Labor	hours	1	0	0	0	0	–1,23	–1,23	–1,23	–1,23	–1,23	–1,23	0	0	0	0
X2	Diesel fuel	liters	0	1	0	0	0	–12,9	–10,1	–10,0	–8,7	–8,65	–3,7	0	0	0	0
X3	Gasoline	liters	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
X4	Lubricants	liters	0	0	0	1	0	0	–0,24	–0,04	–0,07	–0,19	–0,05	0	0	0	0
X5	Chainsaw	PSH	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
X6	Excavator	PSH	0	0	0	0	0	1	0	0	0	0	0	0	0	–0,021	0
X7	Stone crusher	PSH	0	0	0	0	0	0	1	0	0	0	0	0	0	–0,066	0
X8	Grader	PSH	0	0	0	0	0	0	0	1	0	0	0	0	0	–0,032	0
X9	Front loader	PSH	0	0	0	0	0	0	0	0	1	0	0	0	0	–0,118	0
X10	Compactor	PSH	0	0	0	0	0	0	0	0	0	1	0	0	0	–0,025	0
X11	Dump truck	PSH	0	0	0	0	0	0	0	0	0	0	1	0	0	–0,204	0
X12	Trailer	PSH	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
X13	Timber lorry	PSH	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
X14	Preparing one unit of road	m	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
									Technology Matrix A								Y

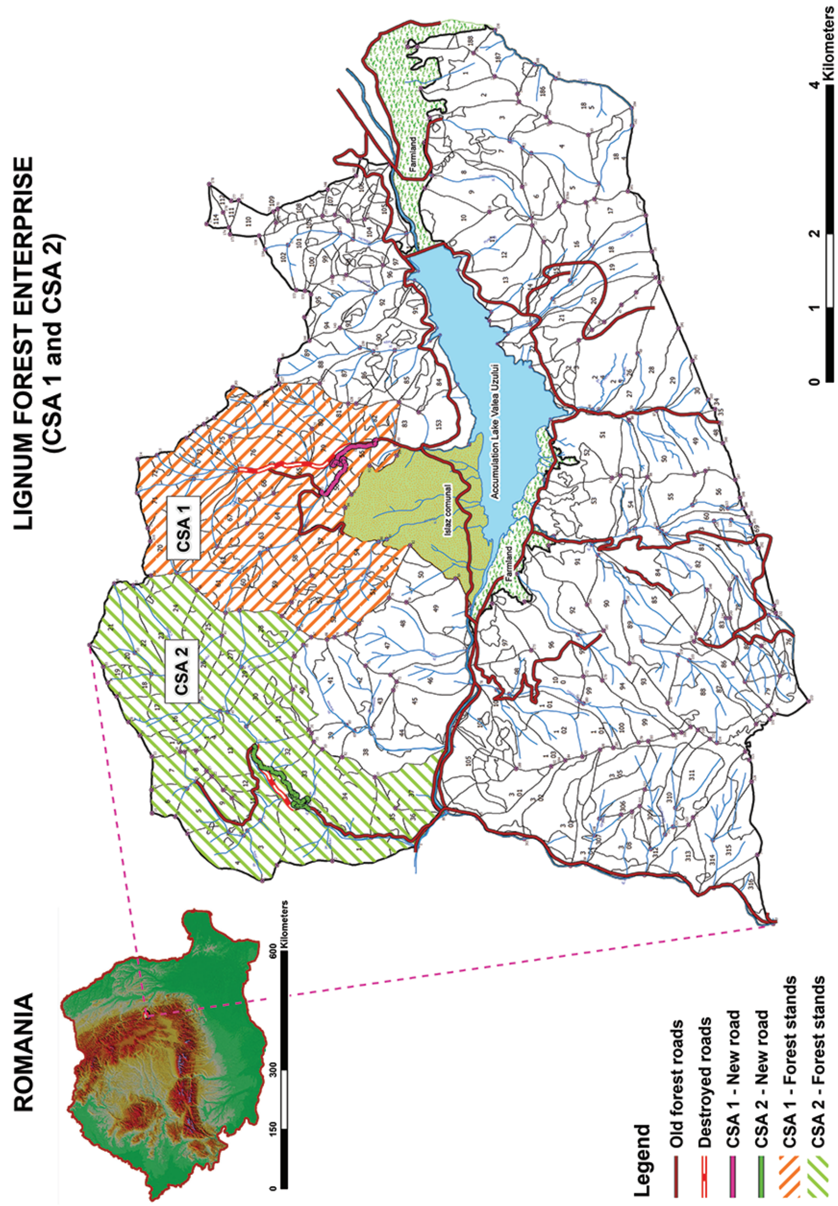


Figure 2 Location of the case study areas (CSA).

which provides drinking water for 27 communities with about 370 000 inhabitants.

The forest enterprise manages about 6 500 ha of mixed broadleaves-coniferous forests, of which 85% have mainly protective functions for water quality. The rotation of forest stands is about 100–110 years for conifers and 110–120 years for broadleaves. The bedrock is of Paleocene age, mainly sandstones, marl schist and alluvial formations, while the most common soil types are brown forest soils (75% of the area) and acid brown soils (25%). The density of forest roads is about 7.6 m ha^{-1}, with roads located mostly along the valleys. Timber extraction is done by tractors and skidders (65% of AAC), forwarders (21%), horse harnesses (8%) and cable yarders (6%). Two case study areas were selected for analysis: CSA 1 – *Forest Road Plopu-Lapos* and CSA 2 – *Forest Road Coporaia* (Table 2).

For each CSA, data of the following machineries used in road construction was collected from the records of the forest enterprise: chainsaw, excavator, stone crusher, grader, front loader, compactor, dump truck, trailer and timber lorry (Table 3). For road maintenance, data was gathered from the records of the maintenance works conducted in 2013 across the entire forest district for old valley forest roads, for the following machinery: backhoe loader, stone crusher, grader, compactor, dump truck and trailer.

2.4.1 CSA 1 – Forest Road "Plopu-Lapos"

The *Plopu-Lapos* forest road was built in 2013 and serves about 842 ha of forests (Figure 2), with an AAC of about 4 000 m^3 y^{-1}. The road has a length of 1.7 km, an average road bed width of 3.5 m and cross stations with an average width of about 7.0 m and 20 m length, located at intervals of 300 to 400 m. The permanent surface occupied by the road is about 1.02 ha, and the pavement structure is of 0.40 m thickness with gravel from on-site provenience. The road was built in moderate terrain conditions, using

Table 2 Key facts about case study areas

Item	CSA 1	CSA 2
Length of the new forest road (m)	1 707	1 968
Forest area served by the road (ha)	841.8	704.0
Current standing volume (m^3)	287 754	252 042
Estimated increment in 30 years (m^3)	151 376	142 032
Estimated gross standing volume after 30 years (m^3)	439 130	394 074
Estimated harvests in 30 years (m^3)	120 000	113 600
Estimated net standing volume in 30 years (m^3)	319 130	280 474

Table 3 Key facts of the machinery used in road construction and maintenance

Machinery	Producer/Model	Weight	Engine Power	Production year
Excavator	Hitachi Zaxis ZX225	22,5 to	110 kw	2006
Stone crusher	Hartl MT 503 BBV	31,8 to	186 kw	1999
Grader	O&K F156A	15,8 to	112 kw	2001
Compactor	Caterpillar CS583 C	14,7 to	72 kw	2000
Bulldozer	Liebherr LR 632	20 to	89 kw	1998
Front loader	Liebherr LR 632	22 to	132 kw	2004
Dump truck	MAN TG 3348	33 to/14 to	353 kw	2008
Timber lorry	Mercedes-Benz Actros 3348	33 to/16 to	350 kw	2007
Trailer	EMPL TLU 4X11	24 to	N/A	1998
Chainsaw	Husqvarna 372 XP	6,1 kg	3,9 kw	2012
Backhoe loader	Terex TX760B	6,8 to	69 kw	2005

a mixed cut-fill profile, with approximately 35% of the road length on low slope terrain and 65% of it on moderate slopes (Table 4). About 99% of the embankment works represented earth mass movements, while only 1% was rock mass movement, with no additional necessary works for stabilizing the slopes (Table 5). Before the new road was built no timber harvesting was

Table 4 Classification of forest roads by slope classes of the terrain in each CSA

	Road CSA1		Road CSA2	
Forest roads	Length (m)	Share (%)	Length (m)	Share (%)
Side slope classes of the terrain				
<25%	600,0	35%	500,0	25%
25–40%	1107,0	65%	510,0	26%
40–55%	0,0	0%	775,0	39%
>55%	0,0	0%	183,0	9%
Total road length (m)	1707,0	100%	1968,0	100%

Table 5 Characteristic of embankment works in each CSA

	Road CSA1		Road CSA2	
Forest roads	Volume (m^3)	Share (%)	Volume (m^3)	Share (%)
Total embankment works (m^3)	8179	100%	24097	100%
– earth mass movement	8104	99%	9880	41%
– rock mass movement	75	1%	14217	59%
Stabilizing support walls (m^3)	0	–	454	–

possible due to lack of access, currently the timber extraction is entirely done by skidders and forwarders.

2.4.2 CSA 2 – Forest Road "Coporaia"

The *Coporaia* forest road was built in 2011 and serves about 704 ha of forests (Figure 2), with an AAC of about 5 250 m^3 y^{-1}. The new road has a length of 2.0 km, an average road bed width of 3.5 m, cross station widths of about 7.0 m and 0.70 m thick gravel pavement from on-site provenience. The permanent surface occupied by this road is about 1.31 ha. The road was built in difficult terrain conditions; about 48% of the road length is located in steep and very steep terrain while 26% of the road length is on moderate slopes (Table 4). For steep and very steep slopes the road was built mostly in full bench profile, while for moderate slopes the mixed cut-fill profile was used. About 41% of the embankment works represented earth mass movements, while 59% was rock mass movement and about 450 m^3 of stones were necessary for stabilizing the slopes with supporting walls (Table 5). Before the road was built, timber extraction was done entirely with skidders on distances up to 3.5 km, while currently used extraction technologies are the skidders and forwarders (65% of the harvested volume) and the cable yarders (35%).

2.4.3 Road Maintenance

According to the Romanian regulations, the road maintenance works should be carried out regularly depending on the category of the forest road and of the amount of timber transported on it. Thus, considering the road network consists mainly of valley forest roads, *Lignum Forest Enterprise* performs road maintenance works at intervals of two years for each forest road. The maintenance works were split in two categories: one referring to pavement works (i.e. road bed and pavement structure reshaping, gravel replacement whenever necessary, leveling and compacting) and another one referring to the drainage system works (i.e. reshaping and cleaning the side ditches and the culverts). The collected data refers to maintenance works performed in 2013 on old valley forest roads which serve a total forest area of 750 ha with an AAC of 7 500 m^3 y^{-1} (35 % thinning, 50% final cuts and 15% sanitary cuts). The total length of repaired ditches was 7 000 m and the total length of reshaped road bed pavement was about 2 500 m. An additional amount of 85 m^3 of gravel was required for reshaping the pavement structure of the road. The gravel was transported from a local gravel deposit located 17 km away from the site.

3 Results

3.1 Machine Utilization Rates

3.1.1 Road Construction

The fuel consumption rates and the machine utilization rates for each phase of the road construction in CSA 1 are depicted in Table 6. For building one meter of road in CSA 1, 0.930 man-hours, 6.19 liters of diesel and 0.772 machine-hours were required. Out of the latter ones about 28% were excavator hours, 27% were dump truck hours and 15% were front loader hours.

The most intensive phases of road construction (in terms of labor, fuel consumption and machine utilization) were the embankments execution and the pavement works. The execution of embankments required about 26% of the labor, 39% of the fuel and 25% of the machinery utilization from the total amounts needed for building the road. For the pavement works, about 62% of the labor, 52% of the fuel and 60% of the machinery utilization were required.

The fuel consumption rates and the machine utilization rates for each phase of the road construction in CSA 2 are depicted in Table 7. For building one meter of road in CSA 2 were necessary about 8.59 liters of diesel and 1.084 machine-hours, out of which 31% were excavator hours, 23% were dump truck hours and 15% were front loader hours. Similar to CSA 1, the most intensive phases of the road construction in terms of labor requirements,

Table 6 Utilization rates of fuel, labor and machinery in CSA 1

Commodities		Preparatory Works	Embankment Works	Drainage system	Pavement works	Total Road Construction	
Labor	hours	0.086	0.239	0.032	0.573	0.930	hours
Diesel fuel	liter	0.192	2.420	0.336	3.242	6.191	liter
Gasoline	liter	0.058	0	0	0	0.058	liter
Lubricants	liter	0.031	0.035	0	0.039	0.105	liter
Chainsaw	PSH	0.042	0	0	0	0.042	PSH
Excavator	PSH	0	0.170	0.026	0	0.217	PSH
Stone crusher	PSH	0	0	0	0.066	0.066	PSH
Grader	PSH	0	0.016	0	0.032	0.047	PSH
Front loader	PSH	0	0	0	0.118	0.118	PSH
Compactor	PSH	0	0.008	0	0.025	0.033	PSH
Dump truck	PSH	0.004	0		0.204	0.208	PSH
Trailer	PSH	0.014	0	0	0	0.014	PSH
Timber lorry	PSH	0.026	0	0	0	0.026	PSH
Road unit	m	1	1	1	1	1	m

Table 7 Utilization rates of fuel, labor and machinery in CSA 2

Commodities		Preparatory Works	Embankment Works	Drainage system	Pavement works	Total Road Construction	
Labor	hours	0.187	0.462	0.024	0.411	1.084	hours
Diesel fuel	liter	0.375	5.080	0.313	2.818	8.586	liter
Gasoline	liter	0.170	0	0	0	0.170	liter
Lubricants	liter	0.090	0.058	0	0.042	0.190	liter
Chainsaw	PSH	0.123	0	0	0	0.123	PSH
Excavator	PSH	0	0.308	0.024	0	0.337	PSH
Stone crusher	PSH	0	0	0	0.075	0.075	PSH
Grader	PSH	0	0.022	0	0.004	0.025	PSH
Front loader	PSH	0	0	0	0.106	0.158	PSH
Compactor	PSH	0	0.014	0	0.048	0.062	PSH
Dump truck	PSH	0.006	0	0	0.173	0.245	PSH
Trailer	PSH	0.018	0	0	0	0.018	PSH
Timber lorry	PSH	0.040	0	0	0	0.040	PSH
Road unit	m	1	1	1	1	1	m

fuel consumption and machinery utilization in CSA 2 were the embankments execution and the pavement works. The execution of embankments required 43% of the labor, 59% of the fuel and 43% of the machine-hours from the total amounts needed for building the road, while the execution of pavement finishing required 38% of the labor, 33% of the fuel and 38% of the machinery utilization.

3.1.2 Road Maintenance

The utilization rates of the machinery used in one road maintenance operation are depicted in Table 8. About 0.5 liter of fuel and 0.072 machine-hours were required for maintaining one meter of road. Hence, during the entire life cycle of the forest road, maintenance works for one meter of road would require about 7.5 liters of fuel and 1.073 machine-hours utilization. The maintenance works of the drainage systems (i.e. reshaping the side ditches and cleaning the culverts) consumed about 60% of the total labor and fuel required for the road maintenance.

3.2 Cost Appraisal

Table 9 shows the structure of the road construction and maintenance effort by type of costs. The total road construction costs were 88.2 € m^{-1} in CSA 1, respectively 119.6 € m^{-1} in CSA 2. The costs reported for road

Table 8 Machinery utilization rates for one process of road maintenance

Commodities	Pavement works	Drainage system	Total Road Maintenance	
Labor	0.029	0.043	0.072	hours
Diesel fuel	0.192	0.308	0.500	liter
Stone crusher	0.002	0.000	0.002	PSH
Grader	0.006	0.000	0.006	PSH
Backhoe loader	0.000	0.043	0.043	PSH
Compactor	0.003	0.000	0.003	PSH
Dump truck	0.016	0.000	0.016	PSH
Trailer	0.002	0.000	0.002	PSH
Road unit	1	1	1	m

Table 9 Structure of the road construction and maintenance costs

	Road construction CSA 1		Road construction CSA 2		Road maintenance	
Cost types	€/m	%	€/m	%	€/m	%
Machinery	22.0	25	37.7	32	1.5	51
Fuel	7.0	8	10.0	8	0.7	24
Labor	48.7	55	67.5	56	0.7	25
Materials	10.5	12	4.4	4	0	0
Total costs (€/m)	88.2	100	119.6	100	2.9	100

maintenance, respectively 2.91 € m^{-1}, are those required for performing one operation. Regarding the road construction, in both CSAs, the labor was the most intensive cost factor, representing about 55% (CSA 1) and 56% (CSA 2) of the total costs, respectively. The second most important cost factor in road construction was the utilization of machineries, with a share of 25% in CSA 1 and 32% in CSA 2 from the total costs. The most important cost factor in road maintenance was the machinery with about 51% of the total maintenance costs, while labor and fuel consumption had similar shares from the total costs, respectively 24% and 25%.

Figure 3 reveals the costs with preparatory works, drainage system execution and pavement works were similar in both CSAs, while the execution of embankments was significantly more costly in CSA 2 than in CSA 1, due to the steeper terrain and hence higher amounts of earth and rock excavations. In respect of road maintenance costs during the life cycle of the road, 60% of the costs are necessary for maintaining the pavement structure of the road and 40% of the costs for maintaining the drainage system. Considering one maintenance operation is carried out in average once at each two years, this means the yearly road maintenance costs are about 1.45 € m^{-1}. In addition, taking into account an yearly interest rate of 3.5%, the total maintenance costs

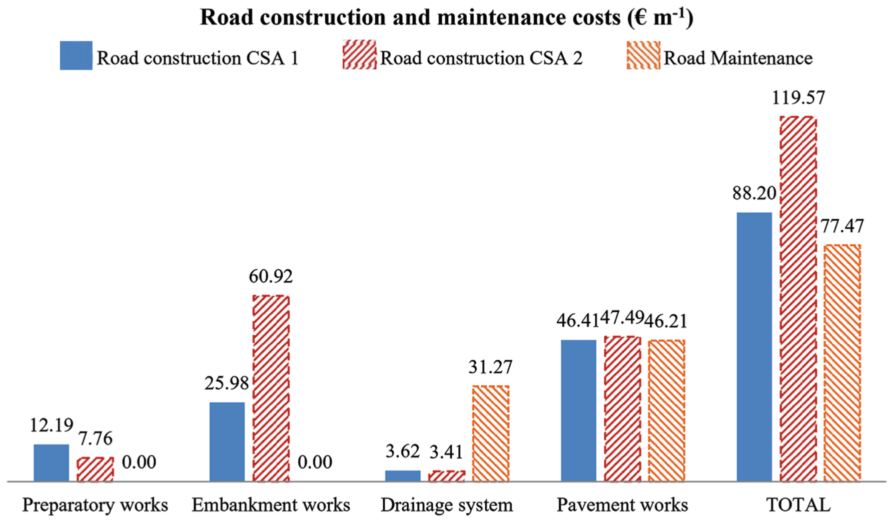


Figure 3 Forest road costs by category of works.

during the life cycle of the forest roads would be 77.5 € m^{-1} (Figure 3). This means that in moderate terrain conditions (i.e. CSA 1 - slopes below 40%) the initial investment costs in road construction would be almost equaled by the maintenance costs (about 88% of the construction costs) during the life cycle of the road, whereas in difficult terrain conditions (i.e. CSA 2 - slopes above 40% and stony material), the maintenance costs of the road would represent about 66% of the initial construction costs.

Table 10 presents the utilization rates, the fuel consumption rates and the system hour costs of the machinery (including fuel and labor costs). Slight variations of the machinery system hour costs were noticed between CSA 1 and CSA 2, respectively between road construction and road maintenance. This was probably because of the effective utilization time of the machineries and due to different operators running specific machineries. It has to be noted the forest enterprise used both local labor and Austrian labor for operating the machinery, the latter case being much more expensive, but however with more experience than local operators.

3.3 Embodied Energy, GHG Emissions and Loss of Productive Land

The most energy intensive phases in road construction are the embankment and the pavement works in both CSAs (Figure 4).

Table 10 Total utilization rates, fuel consumption and costs of machinery

Machinery	Road construction						Road maintenance		
	CSA 1			CSA 2					
	Hours	Fuel (l/h)	Costs (€/h)	Hours	Fuel (l/h)	Costs (€/h)	Hours	Fuel (l/h)	Costs (€/h)
Excavator	370	12.9	138.1	664	13.1	142.0	–	–	–
Stone crusher	112	10.1	134.1	112	10.1	137.8	6	9.7	134.8
Grader	81	9.7	96.5	50	10.0	100.5	14	10.1	95.4
Compactor	57	9.1	142.7	122	8.4	144.9	7	8.7	112.8
Front loader	202	8.7	90.8	311	8.7	101.6	–	–	–
Backhoe loader	–	–	–	–	–	–	299	7.2	27.5
Dump truck	349	3.7	84.1	471	3.7	108.7	40	4.6	30.7
Timber lorry	51	5.4	30.3	79	5.0	21.6	–	–	–
Trailer	24	3.5	32.4	47	7.3	57.9	5	7.3	35.1
Chainsaw	72	1.4	7.7	242	1.4	8.8	–	–	–
Total	1318	–	–	2133	–	–	371	–	–

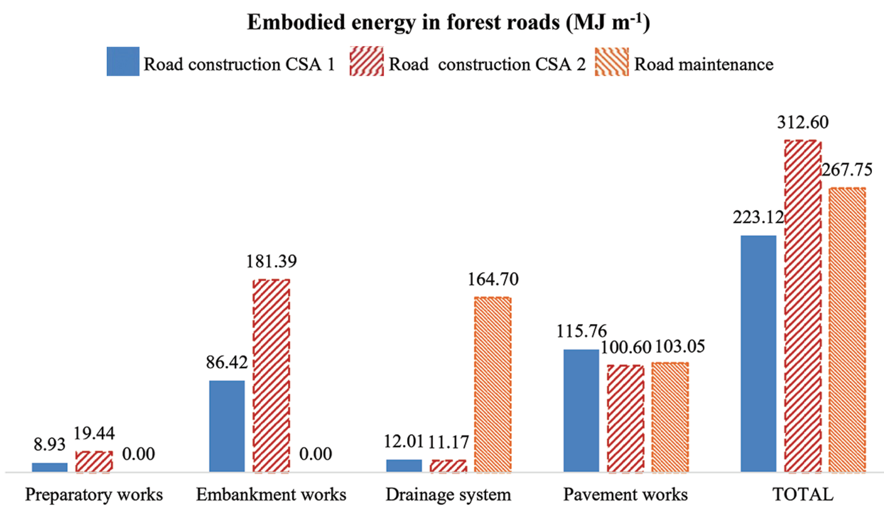


Figure 4 Energy requirements of road construction and maintenance.

Figure 4 reveals a significantly higher energy demand for the embankments execution in CSA 2 (181.4 MJ m^{-1}) compared to CSA 1 (86.4 MJ m^{-1}). This was due to the steeper terrain and more rock excavations in CSA 2 than in CSA 1 (Table 4 and Table 5), which required more machinery utilization. The total amount of energy required for road construction was 223.12 MJ m^{-1} in CSA 1 and 312.60 MJ m^{-1} in CSA 2 (Figure 4). The execution of pavement finishing was the most energy intensive phase in CSA 1, accounting for about 52% of the total energy input, while the most energy intensive phase in CSA 2 was the embankment execution, which accounted for about 58% of the total energy input.

One complete process of road maintenance required about 10.98 MJ m^{-1} for the construction of the drainage system and about 6.87 MJ m^{-1} for the pavement works. Although these figures might seem less energy intensive than the road construction, due to the repetition of this process at regular intervals during the entire life cycle of the road, the energy requirements of the maintenance works might equal or outweigh the energy input required in road construction: 164.70 MJ m^{-1} for drainage system and 103.05 MJ m^{-1} for pavement works. Therefore, the total energy embodied in forest roads due to construction and maintenance would beabout 490.87 MJ m^{-1} in CSA 1 and 580.35 MJ m^{-1} in CSA 2. Considering the allowable cut of each CSA and the life cycle of the forest roads, this means an energy input per cubic meter of timber harvested of about 7.0 MJ in CSA 1, respectively 7.3 MJ in CSA 2.

In what concerns the global warming potential of the forest road construction and maintenance, Table 11 shows the emission rates of $CO_{2eq.}$ per meter of road.

Forest road construction required about 16.6 kg CO_{2eq} m^{-1} in CSA 1 and about 23.0 kg CO_{2eq} m^{-1} in CSA 2. In both cases, the embankment and pavement works accounted together for more than 90% of the total GHG emissions. Considering the AAC and the life cycle of the roads, this means road construction has an environmental footprint of 0.236 kg CO_{2eq} in CSA 1, respectively of 0.251 kg CO_{2eq} in CSA 2 per cubic meter of timber harvested. From the emissions point of view, road maintenance has a lower environmental footprint per one process as such, requiring 0.515 kg CO_{2eq} m^{-1} for maintaining drainage systems and 0.823 kg CO_{2eq} m^{-1} for maintaining the pavement structure. However, due to the repeated interventions during the road life cycle, the CO_{2eq} emission rates of road maintenance are comparable to those

Table 11 Emission rates of CO_{2eq} from road construction and maintenance

GWP emissions of roads		Preparatory works	Embankment works	Drainage system	Pavement works	Total
$CO_{2eq.}$ (kg m^{-1})	CSA 1	0.514	6.479	0.900	8.679	16.573
	CSA 2	1.003	13.599	0.837	7.542	22.983
	Maintenance	0	0	12.345	7.725	20.070

of the initial road construction, one meter of maintained road requiring about 20.1 kg CO_{2eq}. In this study this means that in moderate slope conditions, the level of CO_{2eq} emissions from road maintenance works exceeds the emission levels from road construction in CSA 1 with about 21% and represent about 87% of the road construction requirements in difficult terrain conditions (CSA 2). Thus, road construction and maintenance works combined require about 36.6 kg CO_{2eq} m^{-1} in CSA 1 and 43.1 kg CO_{2eq} m^{-1} in CSA 2, respectively, which means emission rates of about 62.5 t CO_{2eq} in CSA 1 and 84.8 t CO_{2eq} in CSA 2 during the life cycle of the road. Considering the allowable cut in each case study area, these would mean about 0.521 kg CO_{2eq} in CSA 1 and 0.471 kg CO_{2eq} in CSA 2 per cubic meter of timber harvested during the road life cycle.

The permanent surface occupied by the road bed was 10 219 m^2 in CSA 1 and 13 108 m^2 in CSA 2 (Table 12). The loss of productive land due to road construction was about 5.07 m^2 y^{-1} per cubic meter of wood in CSA 1, respectively 5.82 m^2 y^{-1} in CSA 2. Considering the mean annual growth of forests in the study area (6 m^3 ha^{-1} y^{-1}) and that one cubic meter of wood binds about 1.1 tones CO_{2eq} from the atmosphere (Hasenauer, 2014), this means about 6.74 t CO_{2eq} in CSA 1 and 8.65 t CO_{2eq} in CSA 2 are not bound each year due to the loss of productive forest land. Reporting these figures to the road unit, it means that occupying productive forest land with forest roads requires 3.95 kg CO_{2eq} m^{-1} y^{-1} in CSA 1 and 4.40 kg CO_{2eq} m^{-1} y^{-1} in CSA 2.

The CO_{2eq} emissions due to loss of productive land can be only partially compensated by the CO_{2eq} stored in the timber harvested from the road bed clearance (Table 12). For clearing the road bed, about 407 m^3 were harvested in CSA 1 and 297 m^3 in CSA 2, which is equivalent to 447.7 CO_{2eq} and 326.7 t CO_{2eq}, respectively. Considering that approximately 40% of the harvested timber is used for wood products and 60% as energy wood by

Table 12 Impact of road bed clearance on CO_{2eq} emissions

Index	Item	CSA 1	CSA 2
1	Cleared road bed surface (ha)	1.02	1.31
2	CO_{2eq} emissions due to loss of productive land (t CO_{2eq})	202.2	259.5
3	CO_{2eq} from timber harvest road bed (t), of which:	447.7	326.7
4	– stored in wood products (t CO_{2eq})	179.1	130.7
5	– emissions to atmosphere (t CO_{2eq})	268.6	196.0
6	CO_{2eq} balance of the road bed clearance (t CO_{2eq}) [(6) = (4) – (5) – (2)]	–291.7	–324.8

Table 13 Impact of lost productive land on CO_{2eq} emissions during road life cycle

Index	Item	CSA 1	CSA 2
1	Total CO_{2eq} of current standing volume (t CO_{2eq})	316 530	282 750
2	Total CO_{2eq} of timber harvested in 30 years (t CO_{2eq}), of which:	132 000	124 960-
3	– stored in timber products (t CO_{2eq})	52 800	50000-
4	– emissions in atmosphere by energy wood (t CO_{2eq})	79 200	84960-
5	CO_{2eq} of net standing volume in 30 years (t CO_{2eq})	351 040	308 520-
6	CO_{2eq} balance of the road bed clearance (t CO_{2eq})	–291.7	–324.8
7	CO_{2eq} balance of road construction and maintenance (t CO_{2eq})	–62.4	–84.8
8	CO_{2eq} balance of the opened forest area (t CO_{2eq}) [(8) = (7) + (6) + (5) + (3) – (4)]	324 285	273 150

the forest enterprise, this means during the life cycle of the forest roads approximately 130.7 t CO_{2eq} in CSA 2 and 179.1 t CO_{2eq} in CSA 1 can be stored in wood products, the rest being released back in the atmosphere through the burning process. Table 12 reveals that occupying productive forest land with roads means a net loss of 291.7 t CO_{2eq} in CSA 1 and 324.8 t CO_{2eq} in CSA 2.

Notwithstanding, the net CO_{2eq} emissions due to loss of productive land are insignificant when compared to the amount of CO_{2eq} stored in the growing stock of the opened forest area. Table 13 shows the balance of CO_{2eq} due to the loss of productive land occupied by the roads during their entire life cycle for the forest area opened by the road construction in both CSAs. The CO_{2eq} balance was calculated as an algebraic sum of the CO_{2eq} gains (i.e. current standing volume, increment during the life cycle of the road, storage in wood products) and CO_{2eq} losses (i.e. emissions in atmosphere by combustion of energy wood). The CO_{2eq} emissions due to machinery utilization in timber harvesting were not included in this analysis.

4 Discussions and Conclusions

Forest road construction is an intensive process in what concerns machinery utilization, labor required, energy input and GHG emissions. The most energy intensive processes in road construction reported in this study were the embankment and the pavement works, accounting for about 90% of the total energy requirements in each CSA. The most intensive energy consumers and CO_2 emissions generators were the excavator, the dump truck and the front loader, accounting for about 70% of the total necessary machine utilization hours in each case study area.

On the other hand, road maintenance works are also energy intensive. Although one event of road maintenance is not so energy demanding (about 17.85 MJ m^{-1}) compared to road construction, the total energy required for maintenance works during the life cycle of the road (267.75 MJ m^{-1}) outweighs with about 20% the energy requirements for road construction in CSA 1 and represents about 85% of these in CSA 2. Basically, this means that maintaining valley forest roads over a life cycle of 30 years is almost as much energy intensive as the road construction, especially because of the number of repeated interventions. This is due to the well-known fact that valley forest roads are susceptible to more damages than slope roads, due to their vicinity to the water courses, particularly during spring and heavy precipitation season (i.e. snow melting and torrential flows). Therefore, it would be better from the point of view of energy input and GHG emissions to reduce the number of maintenance operations. This could be the case of road networks with more slope roads rather than with valley roads.

The total energy embodied in forest roads (construction and maintenance) was 490.87 MJ m^{-1} in CSA 1 and 580.35 MJ m^{-1} in CSA 2, respectively. In comparison, Heinimann (2012) estimated energy input rates for road construction and maintenance between 315 and 735 MJ m^{-1} road, depending on the side slope variation, while Whittaker et al. (2011) reported energy requirements of 403 MJ m^{-1} for road construction and 102 MJ m^{-1} for road maintenance, including the requirements of machine manufacture and maintenance. However, all these figures should be cautiously interpreted, looking at the characteristics of each study layout (i.e. topographical conditions, definition of the system borders).

One particularly important observation is that in this study the amount of fuel consumed in road construction (6.19 liters m^{-1} in CSA 1 and 8.58 liters m^{-1} in CSA 2) was almost similar to the amount of fuel needed forroad maintenance (7.5 liters m^{-1}) during the life cycle of the forest road. Thus, it can be underlined that the quality of the planning process and of the construction of forest roads plays a crucial role in the future running costs of a road network. Slope forest roads are easier and less costly to maintain than valley roads. Loeffler et al. (2009) estimated fuel consumption rates for road construction in full bench profile varying between 7.7 liters and 18.9 liters per meter of road depending on the side slopes (between 50% and 90%), while Whittaker et al. (2011) reported about 4.7 liters of fuel for building one meter of road, in a case study from Scotland. The terrain conditions and the characteristics of the forest road built in CSA 2 of this study were closer to those assumed by Loeffler et al. (2009) and so were the results regarding the fuel consumption.

The outcomes of this study have showed that road construction and maintenance operations are important sources of GHG emissions. The management practices (i.e. slope roads versus valley roads, share of timber used for timber products versus bio-energy) might have an influence on the environmental footprint of forest roads. However, the quantity of CO_{2eq} emissions from clearing the road bed, building and maintaining the road is insignificant in the equation of the CO_{2eq} emissions balance over the road life cycle. Hence, increasing the density of forest roads with about 2.0 m ha^{-1} in each case study area is worth while from the point of view of GHG emissions balance. Comparable findings were reported in the literature. Loeffler et al. (2009) estimated CO_2 emissions from road construction between 20.9 kg $m^{-1}$and 51.5 kg m^{-1} depending on the side slope variation, while Whittaker et al. (2011) showed about 37.8 kg CO_2 were required for building and maintaining one meter of road. Heinimann (2012) reported CO_2 output rates of road construction and maintenance between 19 kg m^{-1} to 47 kg m^{-1} depending on the terrain side slope conditions. Terrain characteristics have showed a strong influence on the amount of fuel consumption, the required energy inputs and the GHG emissions in this study, too. It was showed that steeper slopes and stonier terrain finally lead to higher environmental burden (i.e. 43.1 kg CO_{2eq} m^{-1} in CSA 2 compared to 36.6 kg CO_{2eq} m^{-1} in CSA 1) and higher road construction costs (i.e. 120 € m^{-1} in CSA 2 compared to 88 € m^{-1} in CSA 1). However, road construction costs are still very high when compared to similar terrain conditions from other countries. For example, in Austria, the road construction costs may vary from 14 € m^{-1} and100 € m^{-1} depending on the terrain slope and stoniness, while the average cost is about 35 € m^{-1} (Ghaffariyan et al. 2010).

The input-output LCA approach proved to be a useful tool for assessing the energy requirements and GHG emission levels of forest roads. Though, setting the system boundaries and the time scale, gathering and analyzing data represent challenging and time consuming tasks. A natural further step of this study would be the accounting of the energy and emissions of different harvesting systems in mountain regions with and without forest roads, in order to see the impact of forest infrastructure development on the environmental footprint of harvesting operations.

5 Acknowledgments

The authors would like to thank Hendrik Schubert and Constantin Vasilică from *Lignum Forest Enterprise* for their support in data collection and feedback during data analysis. We would also like to thank the two anonymous reviewers for their valuable comments and suggestions.

References

[1] Abrudan, I. V., Marinescu, V., Ionescu, O., Ioras, F., Horodnic, S. A., and Sestras, R. 2009. Developments in the Romanian forestry and its linkages with other sectors. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 37(2):14–21.

[2] Borz, S. A., Dinulica, F., Birda, M., Ignea, G., Ciobanu, V. D., Popa, B. 2013. Time consumption and productivity of skidding silver fir (*Abies alba* Mill.) round wood in reduced accessibility conditions: a case study in windthrow salvage logging from Romanian Carpathians. *Annals of Forest Research* 56(2):363–375.

[3] Bosner, A., Poršinsky, T., and Stankić, I. 2012. Forestry and life cycle assessment. P. 139–160 in *Global perspectives on sustainable forest management*, Dr. Clement A. Okia (Ed.). InTech, ISBN: 978-953-51-0569-5.

[4] Berg, S. and Karjalainen, T. 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. *Forestry* 76(3):271–284.

[5] Berg, S. and Lindholm, E.-L. 2005. Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production* 13:33–42.

[6] Coulter, E. D. 2004. *Setting forest road maintenance and upgrade priorities based on environmental effects and expert judgment*. PhD Thesis, Oregon State University, Corvallis, 199 p.

[7] Enache, A., Kühmaier, M., Stampfer, K., Ciobanu, V. D. 2013. An integrative decision support tool for assessing forest roads options in a mountainous region in Romania. *Croatian Journal of Forest Engineering* 34 (1):43–60.

[8] Ghaffariyan, M. R., Stampfer, K., Sessions, J., Durston, T., Kuehmaier, M., Kanzian, C. (2010): Road network optimization heuristic and linear programming. *Journal of Forest Science* 56(3): 137–145.

[9] Heinimann, H. R. and Maeda-Inaba, S. 2003. Quantification of environmental performance indicators EPIS for forest roads. In: Proceedings of Austro 2003: *High Tech Forest Operations for Mountainous Terrain*, Schlaegl, Austria, 13 p.

[10] Heinimann, H. R. 2012. Life cycle assessment (LCA) in Forestry – State and Perspectives. *Croatian Journal of Forest Engineering* 33(2): 357–372.

[11] Holzleitner, F., Kanzian, C., and Stampfer, K. 2011. Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. *European Journal of Forest Research* 130:293–301.

[12] Johnson, L. R., Lippke, B., Marshall, J. D., and Comnick, J. 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. *Wood and Fiber Sciences* 37:30–46.

[13] Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.-J., Eggers, T., Lapvetelainen, T., and Kaipainen, T. 2003. Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. Forest Policy and Economics 5: 141–155.

[14] Klvac, R., Fischer, R., and Skoupy, A. 2012. Energy use of and emissions from the operation phase of a medium distance cableway system. *Croatian Journal of Forest Engineering* 33(1):79–88.

[15] Loeffler, D., Jones, G., Vonessen, N., Healey, S., and Chung, W. 2008. Estimating diesel fuel consumption and carbon dioxide emissions from forest road construction. In: Proc. *Forest Inventory and Analysis (FIA) Symposium 2008* RMRS-P-56CD, McWilliams et al. (Ed.), Fort Collins, 11 p.

[16] Meister, G. (1995): Eco-balances in the pulp industry: assessment of environmental impacts. P. 107–114 In: Proc. of the *International Workshop "Life cycle analysis – a challenge for forestry and forest industry"*, Hamburg, Germany.

[17] Michelsen, O., Solli, C., and Stromman, A. H. 2008. Environmental impact and added value in forestry operations in Norway. *Journal of Industrial Ecology* 12 (1): 69–81.

[18] Mills, K. (2006): Environmental performance measures for forest roads. P. 291–300 In: Proc. of the *29th Council on Forest Engineering Conference*: *"Working globally – sharing forest engineering challenges and technologies around the world"*, Coeur d'Alene, Idaho.

[19] Olofsson, P., Kuemmerle, T., Griffiths, P., Knorn, J., Baccini, A., Gancz, V., Blujdea, V., Houghton, R. A., Abrudan, I. V., and Woodcock, C. E. 2011. Carbon implications of forest restitution in post-socialist Romania. *Environmental Research Letters* 6: 045202, 10 p.

[20] Olteanu, N. 2009. Considerations regarding the optimum density in Romanian forests. P. 701–708 In: Proc. of the *Biennial International Symposium "Forest and Sustainable Development 2008"*, Transilvania University of Brasov.

[21] Popovici, V., Bereziuc, R., and Clinciu, I. 2006. Considerations regarding the enhancement of the forest road network for opening up the forests. *Revista Padurilor* 121(6):19–21.

[22] Richter, K. (1995): Life cycle analysis of wood products. P. 69–77 In: Proc. of the *International Workshop "Life cycle analysis – a challenge for forestry and forest industry"*, Hamburg, Germany.

[23] Seppala, J., Melanen, M., Jouttijarvi, T., Kauppi, L., and Leikola, N. 1998. Forest industry and the environment: a life cycle assessment study from Finland. *Resources, Conservation and Recycling* 23: 87–105.

[24] Sharrard, A. L. 2007. Greening Construction Processes Using an Input-Output-Based Hybrid Life Cycle Assessment Model. *PhD thesis,* Carnegie Mellon University Pittsburgh, Pennsylvania, 343 p.

[25] Stanescu, R. C. 2012. Research concerning production technologies and properties of biofuels for vehicles. *PhD Dissertation*, Transilvania University of Brasov, Romania.

[26] Treloar, G. J., Love, P. E. D., and Crawford, R. H. 2004. Hybrid life-cycle inventory for road construction and use. *Jour. of Constr. Eng. and Manag.* 130(1):43–49.

[27] Whittaker, C., Mortimer, N., Murphy, R., and Matthews, R. 2011. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in UK. *Biomass and Bioenergy* 35: 4581–4594.

[28] World Bank 2012. Functional Analysis of the Sector Environment and Forests in Romania – Vol. 1 & 2. – Final Report, 66 p.

Biographies

Adrian Enache is a research associate at the Institute of Forest Engineering from the University of Natural Resources and Life Sciences (BOKU) –Vienna, Austria. His work focuses on efficiency gaps analysis and multiple criteria decision making in timber harvesting and road network planning in mountain forests (ARANGE project). He holds a doctor degree in forestry (*Transilvania* University of Brasov – UNITBV, Romania, 2013), a master degree in mountain forestry (BOKU, 2009), a certification in project management (CODECS, 2007) and a diploma engineer degree in forestry (UNITBV, 2005). Since 2011 he is enrolled in a PhD program at BOKU.

Karl Stampfer is professor at the Institute of Forest Engineering at BOKU, Vienna. His expertize is related to the multi-dimensional aspects of the wood supply chain (i.e. timber harvesting, road network planning, logistics, cable yarding, ergonomics). He holds a doctoral degree in forestry since 1996 (BOKU) and his habilitation was in 2002 (BOKU). He received several international awards and he is member in numerous international professional societies (i.e. IUFRO, Austrian Association for Agricultural Research, Croatian Academy of Forestry Sciences). Since 2003 he is the chairman of FORMEC - International Symposium on Forestry Mechanization.