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A risk index for multicriterial selection of a logging system with low environmental impact

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ABSTRACT

Setting up the working stages in forest operations is conditioned by environmental protection and forest health requirements. This paper exposes a method for improving the decision-making process by choosing the most environmentally effective logging systems according to terrain configuration and stand characteristics. Such a methodology for selecting machines or logging systems accounting for environment, safety as well as economics, becomes mandatory in the context of sustainable management of forest with multiple functions.

Based on *analytic hierarchy process* analysis the following classification of the environmental performance for four considered alternatives was obtained: skyline system (42.43%), forwarder system (20.22%), skidder system (19.92%) and horse logging system (17.43%).

Further, an environmental risk matrix for the most important 28 risk factors specific to any work equipment used in forest operations was produced. In the end, a multicriterial analysis generated a *risk index RI* ranging between 1.0 and 3.5, which could help choosing the optimal combination of logging system and logging equipment with low environmental impact.

In order to demonstrate the usefulness of the proposed approach, a simple application in specific conditions of a harvesting site is presented.

1. Introduction

Forest management for multiple functions means, among other things, using variable retention cutting systems (shelterwood, group or single tree selection) instead of clearcutting, that raises new challenges both for foresters and loggers. Therefore, modern forestry must combine two often conflicting objectives: minimizing the damages produced to valuable trees left on site including the advanced natural regeneration, while maintaining a financial efficiency of harvesting operations. Under such circumstances, the interventions in the forests should consistently take into account a principle of sustainability and environmental protection in forestry: what remains in the forest is more important than what has been harvested. Therefore it becomes mandatory to use a technology, adapted to each situation as much as possible. As a result, the logging solution chosen for a specific site must take into account simultaneously the remaining trees in the stand, the soil, and good conditions for natural regeneration; in other words, not only economic *efficiency*, but also *sustainability*.

Previous studies have analyzed the environmental impact caused by forestry operations, mainly due to differences in local conditions and harvesting methods (Michelsen et al., 2008; Reyer, 2009; Tsioras and Liamas, 2010).

The process of timber harvesting is carried out in a succession of interrelated operations, including off-road transport (timber extraction), a task with many limitations in terms of environmental protection effectiveness. A combination of different types of harvesting machines able to complete the whole harvesting process defines a logging system. Any harvesting system that uses an extraction machine or equipment (skidder, forwarder, agricultural tractor, ATV, horses) driven into the forest is referred to as ground-based harvesting. The yarders (cable logging) or helicopters (aerial logging) are also options for timber extraction, more environmentally-friendly but with some technological constraints and with higher costs in many cases. Any particular model of tools, equipment or machine used to harvest an area, as individual component of the system, or the harvesting method, can be changed without changing the type of the logging system.

The decision to use a particular equipment or machinery for forest operations can be made at different steps in time, as shown by MacDonald (1999):

- when purchasing a new equipment, according to the long-term working conditions, in order to find a trade-off between cost and reliability;
- when setting up the harvesting layout, according to the conditions of the hauling trails and location of the trees to be harvested;
- by forest managers who have to plan simultaneously more harvesting operations;

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- when the forest supervisor or contractor designs and finalizes in the field the hauling layout, assigning specific logging equipment to be used on suitable sites.

At any stage of these analyses, the decision maker is looking for a fair method to balance the environmental impact, effectiveness and risks brought about by each type of equipment used for the operations.

A multicriterial analysis may indicate which logging system is appropriate, able to reduce the risk of undesired events, having in mind that each harvesting site shall be organized to meet environmental constraints (including protection for remnant trees and seedlings), labor health and safety and economic efficiency. These goals can be achieved only if the logging system and associate equipment is selected according to terrain and stand conditions, providing the increase of *eco-efficiency* that is the ability to produce goods or services without major negative environmental effects (Schmidheiny, 1992).

It is widely acknowledged that logging systems with low environmental impact are well supported by theory (Dykstra and Heinrich, 1997) but, unfortunately, their cost is too high for being affordable (Abrudan, 2012). As a result such systems are seldom effectively applied in practice. No doubts, thinking only in terms of short-term economic efficiency and ignoring the other impacts has some major drawbacks. The most important are the expensive post-harvest restoration measures and the opportunity cost associated with the harvesting of low quality trees in the future.

It has been noticed that the interest to reduce harvesting damages decreases when the mechanization level increases (Furuberg Gjetjernet, 1995) and the frequency and severity of logging damage depend on forest conditions and treatment type at least as much as on technological choices (Spinelli et al., 2010). Selecting an equipment improper for stand conditions can lead to unacceptable effects such as high risk of work accidents or some additional operating costs paid to comply with environmental rules and timber harvest regulations. On a longer term, the most undesirable side-effect is the decrease of bioproductivity of stands affecting their future growth potential (Bustos et al., 2005; Reyer, 2009). Therefore, a methodology for selecting the most appropriate logging machines must rely simultaneously on economic and environmental criteria (Bustos et al., 2005; Tsioras and Liamas, 2010).

The objective of this work is to develop a reliable method for selecting both the logging system and a particular harvesting machine or equipment, having regard to the environmental risk assessment.

2. Method

The study has two stages: a logging system selection procedure, based on *analytic hierarchy process* (AHP) analysis and, secondly, a multicriterial analysis of the environmental risk matrix, used to select the optimal logging machine with reduced environmental impact.

Many multi-criteria decision-making applications in forestry and environmental sciences were done in the last years, including harvest planning, forest biodiversity conservation, forest management sustainability, afforestation, regional planning, and forestry industry (Shiba, 1995; Schmoldt and Peterson, 2000; Qureshi and Harrison, 2003; Coulter et al., 2006; Huang et al., 2011). An extensive survey of the literature on multiple criteria decision-making with main contributions to the broad field of forest management planning is provided by Diaz-Balteiro and Romero (2008), pointing out a high frequency of works that have used the AHP approach.

2.1. The logging system selection

The method known as *analytic hierarchy process* (AHP) is a comprehensive framework available to managers to aid in setting priorities on a system-wide, multicriterial basis. It was developed by Thomas L. Saaty (1990, 2001, 2008) and consists of a decision substantiation process when the problem can be structured through a ranking of criteria and alternatives, and choosing an optimal variant of action depends on how each possible alternative can affect a number of relevant attributes or variables. This method renders subjective assessments of relative importance of the criteria into a linear set of weights.

As shown in Table 1, for applying AHP in the analyzed case, qualitative and quantitative criteria are compared to determine the weights and priorities in order to substantiate the relative positioning of alternatives. The criteria are actually the main factors of influence in choosing the appropriate harvesting systems and in the activities organizing in the context of limiting the environmental impact: Terrain (T), Timber characteristics (TC), Harvest techniques (HT), Weather conditions (W), Environmental restrictions (E), Organization and personnel (O) and Technical–economic factors (TE).

Sub-criteria with direct or indirect environmental impact, considered representative in forest operations, were included within each criterion. It is important to note the direction of change in order to optimize (increase in the criteria of maximum and decrease in the ones of minimum).

Not included in this study, "capital investment" or "acquisition cost of the basic equipment" also belongs to the category of technical–economic factors, but it will be considered for the comparative analysis of

Table 1
The criteria and sub-criteria considered for applying *analytic hierarchy process* to select the most suitable logging system with reduced environmental impact. Words in italic highlight sub-criteria with direct environmental impact.

Criteria	Sub-criteria
1. Terrain (T)	
	1.1 (*SC*) *Slope category*
	1.2 (GR) Ground roughness
	1.3 (*GBC*) *Ground bearing capacity*
2. Timber characteristics (TC)	
	2.1 (*TS*) *Tree size* (*dendrometric parameters*)
	2.2 (*VHA*) *Volume per hectare and dispersion*
	2.3 (TQ) Timber quality (percentage of superior assortments)
3. Harvest techniques (HT)	
	3.1 (*LM*) *Logging method*
	3.2 (*TD*) *Primary transport distance*
	3.3 (*ELR*) *Extent of logging trails/strip roads*
	3.4 (PDT) Preferred direction of primary transport
4. Weather conditions (W)	
	4.1 (*RF*) *Rainfall intensity–duration–frequency*
	4.2 (*SD*) *Snow depth*
	4.3 (*FD*) *Frost depth in soil*
	4.4 (WF) Wind speed frequency
5. Environmental restrictions (E)	
	5.1 (*SA*) *Presence of environmentally sensitive areas*
	5.2 (*NGP*) *Nominal ground pressure of forestry equipment*
	5.3 (ES) Type of extraction system (locomotion system)
	5.4 (*OD*) *Overall dimensions of machinery/equipment*
	5.5 (*MT*) *Mode of transport* (*off/partly/fully in contact with the ground*)
6. Organization and personnel (O)	
	6.1 (*SL*) *Skill level and experience of machinery operators*
	6.2 (EXP) Experience of logging contractor
	6.3 (ME) Modes of employment and crew size
	6.4 (ES) Ergonomics-related and safety hazards features
	6.5 (LC) Labor cost (per hour or per cubic meter)
7. Technical–economic factors (TE)	
	7.1 (MP) Productivity of machinery/equipment
	7.2 (UPC) Unit production cost range
	7.3 (STP) Standing timber price
	7.4 (*FC*) *Consumption of fuels and lubricants*