Title: An integrated multi-criteria decision analysis and optimization modeling approach to spatially operational road decisions

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Abstract

This study developed a generic cost-effective approach for spatially explicit decision support involved in the allocation of road repair treatments under mountainous conditions. The approach begins with an assessment of the existing road conditions in order to identify the extent of environmental impacts and to set rehabilitation priorities in a subjective manner of group decision making. An integer programming model is, therefore, formulated by integrating expert knowledge with operational costs to guide repair schedules and repair regimes required to each segment at the operational planning level. To demonstrate the model performance, we applied it to a case study comprising 289 km of paved roads in the central highlands of the Hyrcanian forests, in the northern part of Iran. Sensitivity of inputs such as weights verification, budgetary limitations, and rehabilitation weights were tested. Results of the subjective analysis showed that 76% of the road analyzed in these forests must be prioritized to receive treatments as intended for forest logistic purposes. Incorporating the extent of environmental impacts into operational costs provided an optimal tradeoff curve caused by selecting an appropriate treatment for each segment across the road network. The approach demonstrate here can be used to design detailed alternative solutions for addressing spatially road decisions under various terrain conditions.

Key words: spatial road decision, upgrading, environmental impacts, uncertainty, tradeoffs curve, optimization

1. Introduction

Forest roads are an integral part of the comprehensive management of natural resources. Traditionally, their services have been severely limited to singular functions such as access to forest resources, allowing forest operations, and the transportation of wood, among others. Management objectives in today's forest planning models are diverse and complex. Increasing the importance of multi-functionality role of forests has radically shifted the conventional management of forest roads from a single-criterion objective (e.g., treating roads to save capital investment) to a multiple-criteria objective (e.g., inclusion of environmental impacts or non-timber products into the formulation of management activities). Therefore, management of active forest road transportation is not an exception (Stückelberger et al. 2006; Ananda and Herath, 2008).

Forest roads have been found to affect adjacent environments with forest management activities (Richards and Gunn, 2003). They are responsible for the majority of potential and actual impacts, such as hillslope failures, soil erosion and other negative ecological effects. These impacts can vary widely over the useful life of roads, depending on the design standard and the terrain on which they are crossed. Perhaps the most significant impact of forest roads is on water quality, due to demolished watercourses and blocked streams during spring melts or after heavy rainfall, resulting in acute deposition of downstream sediment to aquatic resources (Bettinger et al. 1998; Madej et al. 2006). These impacts can be intensified through improperly decisions made in the design, construction, and restoration stages of forest road networks.

With this in mind, following road construction or during its useful life, various geometric design standards (e.g., roadway width, steepness of cutbanks or fillslopes, drain systems, *etc*.) will deteriorate over time and no longer function as intended. Active forest roads are subsequently maintained or upgraded to a higher standard, and some of them may be left untreated or routinely deactivated (Anderson et al. 2006; Weaver and Hagans 2007). Demand for these treatments is influenced by a variety of factors, such as current status of the road, quality or intensity of previous restoration treatments, intended use, available resources, and other strategic objectives.

One of the key challenges face road managers is how to maintain road systems cost-effective for meeting all forest services, remarkably in resource-constrained environments, increase environmental regulations and other social desires (Luce and Black, 2001), while ensuring all security and mobility conditions during the life of roads across the road network.

Various road segments (the smallest road unit bounded to receive a particular treatment) exist in different rehabilitation states until they are restored to their intended design standards with associated costs. The difficulty of finding individual roads or a set of road segments that need to be rehabilitated with the best class of treatments can overwhelm the decision-making process.

In accordance with these decisions, many factors and constraints must be considered from a variety of perspectives, even for a very small illustrative problem (Stückelberger et al. 2006). This is particularly important in steep slope areas where the terrain is notoriously unstable and prone to mass road failures and surface erosion (Madej et al. 2006; Thompson and Sessions 2010).

The other major problem is not only finding an appropriate rehabilitation treatment (selection of activities), but also where (and when) to implement it, combining a growing array of the decision variables amenable to analysis.

Forest practices in mountain regions generally involve competitive objectives (Palma and Nelson, 2014), numerous alternatives and several stakeholders with miscellaneous preferences. This requires that any planning tools and implementations must be able to provide a set of compromising solutions for addressing multiple-forest functions by analyzing massive information of different directions at multiple scales and intensities upfront. This information includes environmental factors (i.e., water quality), physical attributes (i.e., layout of terrain), road design standards (i.e., road gradient), financial incentives (i.e., available resources), and social interests (i.e., stakeholders with conflicting interests) among others. In this context, considering these domains of information into the conventional forest management decision-making process (i.e., single-objective decision tools) can be rather simple when analyzed individually. However, when considered together on a large spatial and temporal scale, make the task more complex and challenging to achieve. This is far from being a trivial task. The complexity arises from the fact that there is no scientifically accepted approach to quantify most of these subjective and/or qualitative objectives. A variety of techniques, however, have been deployed as the solution to address decisions involving forest roads subject to multiple environmental objectives. For instance, Madej et al. (2006), Rackley and Chung, (2007), and Thompson and Sessions (2008) incorporated an estimated erosion rate and sediment delivery, as a proxy of adverse environmental effects on each segment, in the formulation of road repair strategies.

The challenge is that some of these environmental objectives or considerations are more difficult to monetize (Costanza et al., 1997; Rackley and Chung, 2007), while others may even have a numerical value which makes monetary expressions irrelevant. For example, the cost of biotechnical practices to stabilize fillslope is generally estimable, the benefit and drawback of these treatments on entire road networks is difficult to quantify.

To extend the traditional and/or single-criteria decision-making process, some authors have suggested an integration of multiple criteria decision analysis (MCDA) through using one of its common methods, e.g., DEA (data envelopment analysis), AHP (analytical hierarchy process), *etc*. Given a practical design, such an advanced method can analyze a large array of information either with different sources (environmental or ecological), scales (quantitative or qualitative), or intensities (numeric or categorical data) simultaneously (Ananda and Herath, 2008). Another possible option is the use of multi-objective optimization approaches. Stückelberger et al. (2006), demonstrated a bi-objective linear programing model to frame interactions between road repair treatments and deleterious ecological effects at the operational planning level. Much focus has been given to the use of MCDA techniques in natural resource management and it continues to progress (Mendoza and Martins, 2006; Tampekis et al. 2015), mainly due to the increases in a huge number of variables related to the multi-functionality role of forests and the enlargement of conventional decision making problems. Basically, these methods look for a decision problem in a hierarchically form, to determine decision preferences that are influenced by personal values and various priorities, and eventually to compensate competitive objectives for a number of decision alternatives.

There is a considerable modeling approach developed to evaluate forest road transportation for potential environmental impacts (See Bettinger et al. 1998; Tomberlin et al. 2002; Girvetz and Shilling, 2003; Madej et al. 2006; Anderson et al. 2006; Rackley and Chung, 2007; Thompson and Sessions 2010), but few are the application that have considered these impacts in a comprehensive way. Because there is no generic decision method for explicitly quantifying a large part of these impacts and incorporating them into numerical analyses of road rehabilitation treatments. The environmental impacts considered in those studies were limited to a short list, including the risk of erosion, chronic sediment input delivery, and obstacles to aquatic habitat quality. In addition, the sourcing data for these impacts came mainly from historical databases or simulation efforts (e.g., estimating the expected attribute on the basis of previous measurements), largely without or less efforts to validate these databases. For instance, Rackley and Chung (2007) used a computer model, WEPP, to predict expected erosion and sediment delivery, as a proxy of adverse environmental impacts combined with planning decisions for the transportation network. This list can, however, be further expanded to take a few other classes of potential factors to describe environmental harm, such as physical attributes of terrains, road design standards and biological attributes across the road network. Indeed, there is a wealth of knowledge on scheduling of road decommissioning, upgrading, and maintenance using quantitative modeling approaches. It is striking that far too little evidence has been found on implicit selection and tradeoffs between the two major repair activities for active transportation roads (e.g., maintenance is less expensive but has to be done several times, and upgrading is more expensive but can be done less frequently). In addition, there is significant interest in combining quantitative information (cost) with a wide range of qualitative information (subjective or aspatial expert judgements) across the road network to arrive at a compromise solution that analyzes conflicting objectives.

The rest of this paper is organized as follows: Section 2 reviews the literature of operation research contributions in management of forest roads rehabilitation. Section 3 begins with a brief description of the spatial road repair problem. The methodology used in this paper, which contains description of the developed approach, the model validation, and the implementation of the system is described in Section 4. Results are detailed in Section 5. Thereafter, Section 6 is devoted to discuss findings, summarize key points, and propose possible extensions of this work.

1.1. Literature review

In the literature, several optimization models have been reported to address road repair decisions, few of which apparently precluded the extent of harmful environmental impacts in their modeling efforts. Anderson et al. (2006) utilized a dynamic programming model to determine the optimal road class and deactivation strategies based on monetary values, without broadening their formulation to consider environmental impacts. Palma and Nelson (2014) developed a robust model formulation to integrate a multiperiod road-building and harvest scheduling problems in which the tradeoffs across the protection of road construction and the minimum feasibility of timber demand are studied. Flisberg et al. (2014) presented a tactical optimization model in which the objective function measures two costs: the cost of harvesting stands at the roadside and the cost of logistic network for which decisions to road rehabilitation were uncertain.

A combination of the MCDA and spatial analysis has been conceived to manage road repair strategies in the realm of forestry. Tampekis et al. (2015) used the AHP combined with expert opinions to account for adverse environmental impacts of a road network without anticipating any mechanism designed to handle monetary values. The difficulty of analyzing environmental impacts with monetary values is reported in Coulter et al. (2006a). Heuristics search algorithms (simulated annealing and threshold accepting) were adapted to allocate road repair treatments. Coulter at al. (2006*b*) used crisp linguistic terms within the framework of AHP. They used a set of crisp or discrete numerical values to handle pairwise comparisons in order to quantify subjective attributes involved in prioritizing road rehabilitation treatments. Richards and Gunn (2000) defined a penalty function to weight losses of biological productivity, as a function of environmental damage, incurred when inappropriate harvest timings were selected for a tactical road scheduling problem. Girvetz and Shilling, (2003) used the ecosystem management decision support (EMDS) to analyze road systems for potential environmental impacts. The management decisions analyzed were road decommissioned and road remain open without including economic costs for future planning process.

The environmental database in the existing literature described above, most of which was based on expert opinions, which is clearly unable to address uncertainties in the upstream sourcing data and the result obtained by this type of analysis. Boyland et al (2006) contend that using fuzzy definitions instead of crisp judgements can yield stable outcomes that are less sensitive to change. Tomberlin et al. (2002) developed a stochastic dynamic programing model to generate tradeoff curves between maintaining the current status of roads (status quo management) and the cost of road decommissioning. Madej et al (2006) designed a decoupled strategy, based on dynamic programming and genetic algorithms, to consider the effectiveness of rehabilitation policies, however, the study did not analyze the entire road network for future resource transportation. Rackley and Chung (2007) incorporated the environmental impacts (i.e., sediment delivery) of forest roads into an economic analysis for resource transportation planning. Their study not only precluded the costs of road rehabilitation treatments, but also failed to provide a decision mechanism to quantify other environmental factors for economic analysis.

The overall objective of this paper is to develop a cost-effective decision approach by integrating individual models (i.e., a subjective model, and a numerical optimization model) within a hierarchical structure to guide essential road repair treatments of the existing road network at an operational planning level. Specifically, this modeling approach is intended, firstly, to analyze the existing road conditions in order to identify the extent of environmental impacts and set rehabilitation priorities in a subjective manner of group decision-making. Secondly, it uses the information resulting from the previous step, as a proxy of environmental impacts, combined with management costs to analyze the tradeoff curves between the total repair cost and the impact of unfavorable environmental factors; due to selecting different repair treatments. In should be noted that these two models were linked as one unique model thanks to a shared database aimed at simultaneously analyzing existing road conditions and thus projecting possible rehabilitation treatments, either repair schedules or repair regimes, during their service life.

The scientific contributions of this paper are threefold: 1) to develop a group-multicriteria decision framework combined with theory of fuzzy sets (to address uncertainties regarding upstream input data), analyzing existing road conditions from a variety of attributes, 2) to develop entropy-based metrics to validate weighting procedures and, hence, reduce the uncertainty associated with the quality of results provided by the group-multicriteria decision in the absence of expert opinions, and 3) to propose an efficient optimization model, analyzing tradeoffs between total repair costs and the extent of adverse environmental impacts, due to selecting different repair treatments for an operational planning level. The proposed methodology has a generic framework, and applied to a real-case study in the mountainous forests of Iran to which there is no optimization decision support tool to explicitly choose various repair treatments, both spatially and temporally.

2. Planning problem

It is a common practice to leave forest roads transportation open and active after the cessation of timber harvest operations. Once the operation is completed, these gravel-surfaced roads are maintained for use by forest services for firebreaks, silviculture and other multiple-use activities to which access to the forest is required. The problem facing forest road systems in northern Iran typically begins in mid-autumn (e.g., after heavy rains) and continues through the spring months (e.g., after snow thawing). First, the abscission of leaves in mid-fall casts a large quantity of debris into drainage systems, resulting in the risk of clogging ditches or obstructing culvert inlets during the rainy seasons. Second, during the spring breakup, snowmelt occurs quickly, especially in upland and middle mountains. This can cause significant overland flows into nearby drainage systems. More often than not, much of the road surface in these forests is soaking wet due to the high amount of precipitation per year. These conditions are the common causes of deteriorating roads in the north forests of Iran, which can potentially mobilize a massive amount of sediment into nearby streams and yield a lot of turbidity. Moreover, the low quality of paved surfaces, poorly aligned drainage systems, and improper design standards exacerbates the challenges discussed above. Therefore, a considerable budget due would be required each year to maintain the road system efficient to perform its intended services in case of unexpected damage. Indeed, there is a specified budget constrain to maintain the road system serviceable, while ensuring that its design standards function properly throughout the planning horizon.

In Iran, government authorities recently imposed a new forest management policy to reduce annual harvestable volumes on public forest lands over a period of ten years. This is changing; hence, a new analytical decision support tool must be developed in the successful uptake of this policy, and ensures the potential for cost savings, while minimizing the risk of environmental harm on various components of the forest ecosystem.

Given the pervasiveness of this decision, local road managers are looking for a new analytical tool to support spatial decisions involved in allocating road repair treatments at the operational planning level. This tool must be able to efficiently determine the repair schedule (i.e., the time when roads or set of road segments should be treated), and the repair regime (i.e., the repair treatment required for each road segment) for the entire road network under their authority. It is for these reasons that we had to develop a resource allocation model independent of traditional harvest decisions, allows realizing the potential for cost savings in an effective manner.

In a hierarchical forest management plan, it is at the operational planning level that tactical decisions including road decisions are made spatially explicit. An important function of the tactical planning process is to choose explicit schedules for harvesting practices and logistic activities, including road interventions, both spatially and temporally. A typical forest management plan includes several decisions at different planning levels, although the definitions and decisions made at each level are different depending on the problem and the country (Rönnqvist, 2003). The plan often includes two major sub-plans; one for harvesting operations and associated decisions, such as the location of stands to be harvested, the choice of mechanization, *etc*., and the other for logistic activities, such as the locations of wood terminals, construction of new roads, road repair treatments, *etc*. The strategic plan often spans a planning horizon of one or more rotations over a period of one hundred years, whereas tactical planning includes a period of ten years, and typical operational planning normally plans for a period of one year.

Surprisingly, in Iran, there is no specific optimization model developed to optimize decisions and activities involved in mechanical forest management practices, including operational road decisions, and the majority of these decisions were mainly taken upon experiences from the past or the use of historical data.

The current management of road rehabilitation treatments, henceforth, for consistency, status quo management, is undertaken on the need of road segments, virtual inspections (non-destructive) documented during field surveys, and the availability of budget. Road rehabilitation activities are rarely made to comply with harvesting decisions. The main intention of this management plan is to treat the greatest length of roads in order to sustain the continuity of logistic operations without including the effect of environmental impacts in these decisions. A plan like this, in many cases, is not cost-effective, both spatially and temporally. This plan is often scheduled for a period of 10 years in advance, although it can be reassessed when the available budget is projecting for the subsequent year. As has been seen, it is extremely difficult to anticipate the cost of road repair treatments upfront and to determine the timing and location of treatments in this planning approach.

In practice, rehabilitation practices for an active road transportation network can be broadly divided into routine maintenance and road upgrading. Road maintenance treatment keeps the road system at a minimum level of service for travel. It is generally carried out following or in conjunction with harvesting operations within a range of at least one or two years in between. This includes a wide range of practices, such as limiting detrimental impacts on the road surface and its shoulders to prevent erosion due to failure of the drainage system, brush cutting, removing unstable fill and sometimes compaction road surfaces. Road upgrade treatment, in contrast, aimed at improving road design standards to a higher level, such as resurfacing, grading cutbanks, replacing or installing poorly aligned cross drain culverts, sight distance and other engineered structures over a longer period of three to five years. Identify and set repair treatments based on intuitive or subjective information from road inventories is time-consuming and challenging, thus this makes the decision-making process difficult in practice even with intensive inventories. The inventory of existing road transport has been identified as a proactive mechanism to prevent future degradation, suggest possible repair treatments and therefore reduce the total rehabilitation cost. It is often carried out by subjective judgements of a qualified inspector, weekly in the spring or monthly during the autumn. A typical road inventory has to provide several types of site-specific information regarding characteristics of the network, which may impact decisions about repair schedules or repair regimes.

It should be noted that insofar there is no a decent decision tool for selecting routine maintenance and periodic upgrades, considering management costs and a wide range of negative environmental impacts of rehabilitation policies across the road network. Increasing the potential to cause environmental damage requires a higher standard of repair treatment to be implemented on the road network. This consequently increases the cost of road rehabilitation. Therefore, road managers must select a combination of appropriate treatment for various road segments, by weighting the relative benefits of light treatments with lower operating costs compared to more intensive ones with higher operating costs.

We suppose that if entire roads are to be managed in these forests, there are indeed tradeoffs between the timing and location of different repair treatments and the extent of negative environmental impacts. This means that meeting these goals implies compromising the environmental impacts (by allocating an appropriate treatment to the segments under a particular environmental risk), or incurring additional costs (due to the allocation of expensive treatments, which do not need to be rehabilitated with such an expensive treatment).

In this article, we attempt to improve the quality of road repair decisions and provide road managers with an integrated decision support tool to analyze subjective attributes of the road network and make tradeoffs between different road repair treatments.

It should be noted that the intention of this article is not to accurately monetize the environmental costs of variable attributes, rather to adapt a practical mechanism to estimate the magnitude of these impacts and incorporate them into the numerical analysis for optimal road rehabilitation treatments.

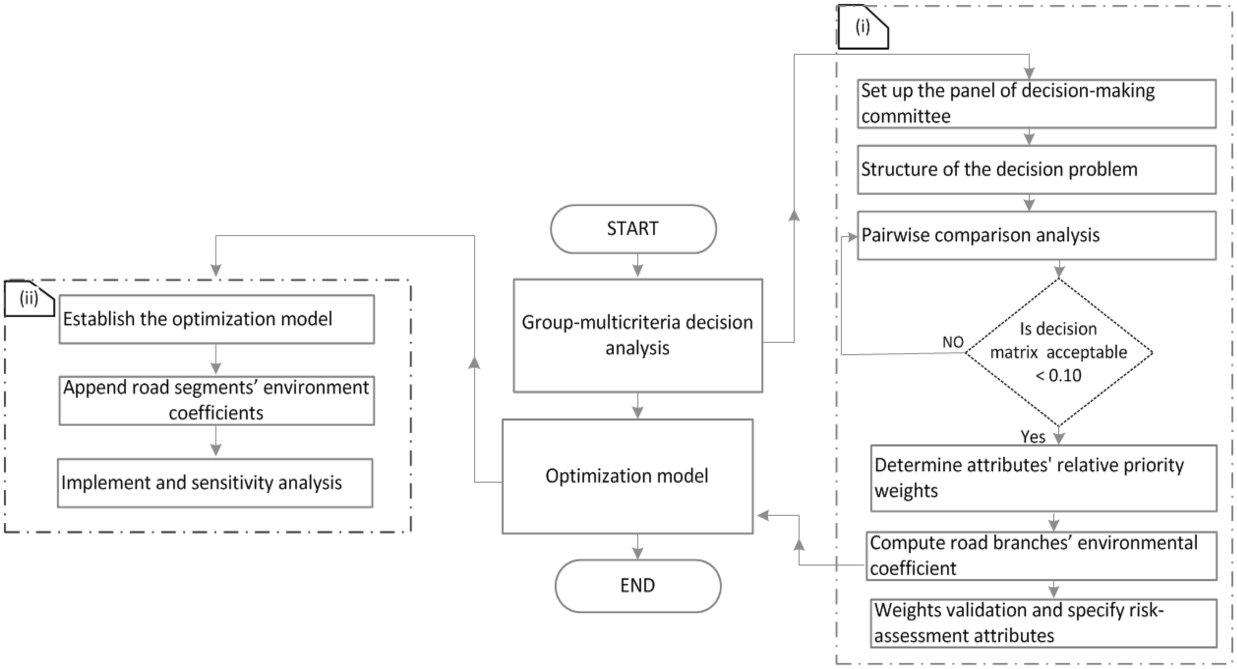
3. Methodology

Figure 1 illustrates the general framework of the integrated modeling approach. The core element of this approach comprises two parts: (i) the group-multicriteria decision making (group-MCDA) used to identify the scope of environmental impacts and to establish rehabilitation priorities in a subjective manner, and (ii) the optimization model used to allocate essential repair schedules and required repair regimes to each segment with simultaneous consideration of monetary and non-monetary attributes for operational planning purposes.

The first part was initiated with: (i.1) the analysis of the decision-making committee, (i.2) the structure of the decision problem and specify its relevant attributes (criteria/subcriteria and factors), (i.3) pairwise comparisons and the development of judgment matrices, (i.4) determine the relative priority weights of decision attributes, (i.5) compute environmental coefficient to road branches, and (i.6) validation of weights and specify risk-assessment attributes.

The second part includes (ii.1) the development of mathematical model, (ii.2) the adjustment of environmental coefficients to road segments as inputs for the optimization model, (ii.3) model solving and the sensitivity analysis of inputs.

[Figure 1]. Workflow of the study: (i) group multicriteria decision analysis and (ii) optimization model



3.1. Group multicriteria decision analysis

3.1.1. Decision-maker analysis

The aim of the decision-maker analysis was to involve relevant experts and to determine the extent of their contribution in the way of analyzing the underlying problem in a group decision making context (Ezzati et al. 2016). In this regard, different professional interests were invited to collaborate in structuring of the decision problem and to identify the significant decision elements coherent with the overall goal. They were also responsible for performing pairwise comparison matrices correspond to all elements of the decision hierarchy (see subsection 3.1.3). The decision committee includes a panel of five experts with knowledge of local conditions for the case in practice (i.e., two research professionals with three field technicians) who have been involved in forest engineering issues for several years.

In collaboration with the decision-making committee, we decomposed the underlying problem into a multi-level hierarchical structure, so that they can focus on a very specific part in the course of analyzing the problem. The panel has consented to respect some principles for selecting the decision elements: 1) thought for technical/logistical factors, including drainage types, road gradient, *etc*. 2) care consideration for road-related environmental concerns, includes distance to a stream, aquatic ecosystems, ground cover, and 3) concern for physical factors, includes hillslope, geologic conditions, slope stability, *etc*. We also reviewed relevant literature, both scientific and technical papers, to identify the range of site types and conditions that were acknowledged by the previous studies for which the overall objective can be fully achieved (Coulter et al. 2006a&b; Thompson and Sessions 2010; Palma and Nelson, 2014; Tampekis et al. 2015; Ezzati et al. 2016).

3.1.2. Structuring of the decision problem

In a generic MCDA, hierarchical decision elements include the overall goal, positioned at the top level, the decision alternatives located at the lowest level, and the decision attributes (i.e., criteria, subcriteria, and factors) are located between these two extremes. In case of several items descend from a particular decision attribute (i.e., criteria, subcriteria, and factors), a cluster could be formed with the aim of condensing the hierarchical decision-model. In this case study, the decision alternatives are equivalent to the road branches (i.e., a set of aggregated road segments). It should be noted that we aggregated a series of road segments belonging to a particular road branch to create coarse decision units and thus avoid a large number of pairwise comparisons with the MCDA process. After completing the MCDA part, the actual definition of road segments was used to compute management costs for the numerical analysis (see the next Section).

In this formulation, the decision elements spread out in all directions and are hierarchically related to each other. A decision hierarchy is a linear top down structure. Figure 2 illustrates a conceptual decision structure composes of goal and decision attributes (i.e., criteria, subcriteria and factors): multitude attributes are positioned inside a cluster.

[Figure 2]. A conceptual decision structure with clusters and associated attributes

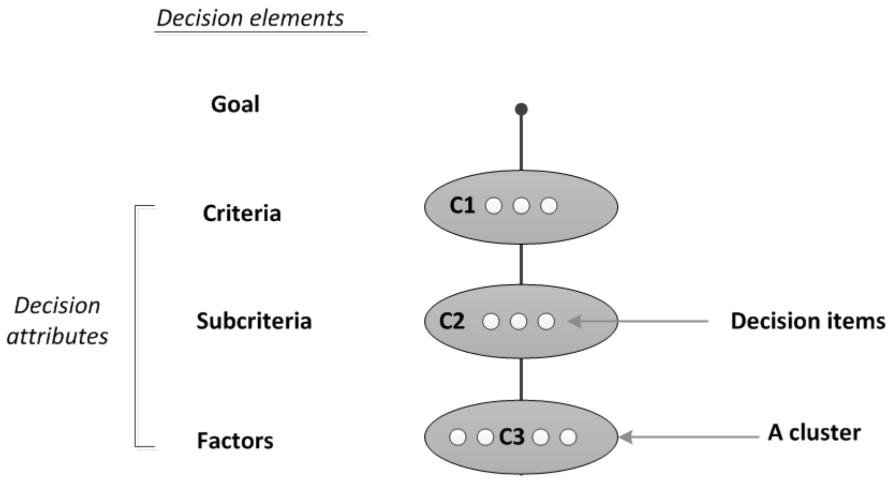
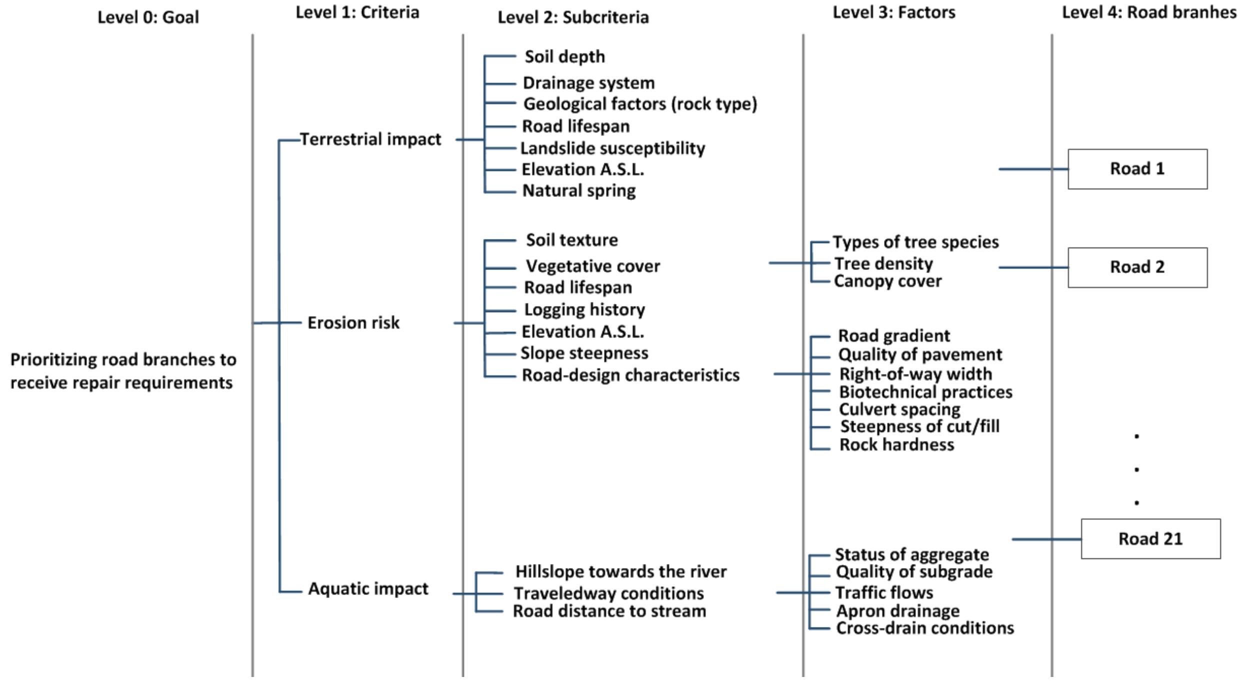


Figure 3 shows a tree-like decision hierarchy, assuming all dependence relationships between elements of the model. The decision problem was hierarchically structured with four levels under the overall goal. Each level was subdivided into multitude clusters with several elements inside. The goal of decision hierarchy defined as ‘evaluating multiple road branches across the road network to receive repair treatments’ subject to a set of environmental attributes.

For the first level, we developed three set of criteria by decomposing the goal into its relevant criteria affecting physical structures of the road network, i.e., ‘terrestrial impact’, ‘erosion and sediment risk’, and ‘aquatic impact’. These three criteria were placed in a cluster. The second level of the hierarchy further subdivided the criteria into specific subcriteria. At this level, seventeen subcriteria were delineated, which grouped into three specific clusters. Cluster no.1 descends from the criterion ‘terrestrial impact’ with seven subcriteria; cluster no.2 descends from the criterion ‘erosion and sediment risk’ with three subcriteria; and finally cluster no.3 descends from the criterion ‘aquatic impact’ with seven subcriteria. For the third level, we determined fifteen factors, by further breaking the subcriteria down into more detailed factors. In order to keep the decision problem amenable, these factors were grouped into three additional clusters (Figure 3). Cluster no.4 descends from the subcriterion ‘vegetative cover’ with three factors, cluster no.5 descends from the subcriterion ‘road design characteristics’ with seven factors, and eventually cluster no.6 descends from the subcriterion ‘traveledway conditions’ with five factors. Associated with this hierarchy, twenty-one road branches (i.e., a set of aggregated segments) were listed on the fourth level. In summary, the decision hierarchy structured with 35 decision attributes along with 21 road branches as spatial decision alternatives.

[Figure 3]. Hierarchical structure of the decision graph proposed for the subjective analysis. A four level of hierarchy is structured under the main goal. Each level is subdivided to a number of clusters. For example, the first level has one cluster with three criteria. The second level has three clusters with multiple items inside; and the third level has three clusters that descended from the subcriteria level at the second level. Associated with these elements at upper levels, road branches are positioned at the bottom of the hierarchy.



3.1.3. Development of pairwise comparison

After developing the hierarchical model, a set of square judgement matrices was generated in the form of a structured questionnaire survey. Table 1 shows a sample of the questionnaire used for collecting pairwise priority choices.

Table 1. A sample of pairwise comparison questionnaire, filled out with verbal scales

Question		Fuzzy expression
Q.1	With respect to the overall goal 'prioritizing road branches to receive repair requirements' what degree of importance do you assign to the criterion 'terrestrial impact'?	Just equal Equally important Weakly important Strongly more important Very strongly more important Absolutely more important
Q.2	With respect to the overall goal 'prioritizing road branches to receive repair requirements' what degree of importance do you assign to the criterion 'erosion & sediment risk'?	Just equal Equally important Weakly important Strongly more important Very strongly more important Absolutely more important
Q.3	With respect to the overall goal 'prioritizing road branches to receive repair requirements' what degree of importance do you assign to the criterion 'aquatic impact'?	Just equal Equally important Weakly important Strongly more important Very strongly more important Absolutely more important

The questionnaire surveys were distributed among members of the decision-making committee. They were mandated to evaluate the decision elements, based on their expert knowledge, and thus collect pairwise comparison matrices, as part of data acquiring. Development of the pairwise comparisons or judgement matrices is performed from the top to bottom. In doing so, the decision-making committee was independently asked to determine the strength of preference or importance of each item versus another, on the importance of a decision attribute or a road branch. The aim of this step was to standardize the model elements and obtain the associated weights.

The number of judgements for each set of comparisons with n attribute is calculated as $n(n-1)/2$. To do so, a criterion is chosen as a base; pairwise comparisons among its relevant subcriteria, situated at a lower level, are carried-out until all criteria are completed. In the same way, a road branch is chosen as base; and pairwise comparisons among its relevant criteria are conducted. This process is repeated for other elements until all pairwise comparisons are completed.

As an example, the criterion ‘risk of erosion and sediment’ is determined by the potential subcriteria among the assertions of: ‘soil texture’, ‘vegetation cover’, ‘geological factors’, ‘slope steepness’, *etc*. The relationship or how these attributes are related to each other is shown on two levels. The criterion is positioned on the first level, while the associated subcriteria are situated on the second level. These subcriteria are formalized in a square matrix and compared with respect to criterion at the first level. To determine the importance of these subcriteria with respect to the criterion ‘erosion and sediment risk’, following question forms the questioner. I) What degree of importance do you assign to subcriterion ‘soil texture’? ii) What degree of importance do you assign to the subcriterion ‘slope steepness’? Other elements of the developed decision hierarchy followed similar trends.

In this study, for a given questionnaire, it was necessary to perform a number of 805 pairwise comparisons, i.e., 210 pairs at the alternative level with 595 pairs at the attribute level, including criteria/subcriteria and factor.

As cited in the introduction, a major benefit of the MCDA is related to its flexibility dealing with inputs of multiple units, intensities or scales. For this instance, slope is measured in per cent, distance is in meter, while vegetative cover is estimated on number of tree per ha. In order to use these data, they must be converted to relative values. Typically, this can be accomplished using either linear discrete scales (Saaty 1980) or fuzzy linguistic scales (Kulak and Kahraman 2005). The discrete scale consists of a unique, single and crisp numerical valuation on a scale of 1 (least important) to 9 (most important) to transform subjective information through pairwise priority choices. A fuzzy number, by contrast, is a class of object with a continuous gradation, between zero and one (gray scales), denotes partial membership in a set.

3.1.4. Determining weights

The AHP was used, as a base method, to quantify subjective information of the group-MCDA (including multiple experts in the evaluation process), and to define priority weight associated with different parameters involved in the evaluation of forest roads for the environmental impacts. Although the AHP procedure is not free of criticism (Mendoza and Martins, 2006), it seems to fit well with the type of problem considered in this study. The reliability of the AHP in the realm of spatially forest planning problems has been well documented (See Kangas and Kangas 2005; Coulter et al. 2006a&b).

The motive for the deployment of fuzzy linguistic scales is based on the fact that the classical AHP, using the discrete scales to cover pairwise priority choices, cannot address uncertainties. First, the traditional AHP method assumes that a decision-maker has to provide a crisp valuation to transform subjective information through pairwise comparisons. In these situations, decision makers might be unable or reluctant to assign crisp values, and hence their preferences are often involved with uncertainties. Second, decision makers have been cognitively limited to express their opinion within threshold boundaries (Saaty's scales) to pairwise priority choices. In fact the choice of human preference has a significant effect on outcomes, and can be a major source of uncertainty in each decision-making process. Since human beings are involved in the decision-making analysis, and their preferences should determine the importance weights for a set of elements, therefore, this makes the fuzzy decision-making necessary.

In this study, therefore, the fuzzy linguistic scales were used to calibrate subjective information to numerical values through pairwise priority choices, as illustrated in Table 2. More specifically, we used symmetric triangular fuzzy numbers (TFNs), as the most common fuzzy expressions to determine weight of elements in the hierarchical matrix. A TFN can, typically, be denoted as a triple $\tilde{A} = (l, m, u)$, in which parameter, *l*, *m* and *u*, corresponds to lower bound, modal-upper, and upper bound, respectively.

Table 2. Triangular fuzzy number (TFN) conversion scales for converting element values to relative scales

Linguistic scale	Triangular fuzzy scale	Reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

As an example, slope of road is a linguistic variable if its value supposed to be stated using typical triangular fuzzy numbers (i.e., low, medium, high), instead of discrete terms (i.e., 0%, 5%, 10%). The associated fuzzy labels use to convert this expression can be expressed as a vector of [2.50, 3.00, 3.50]. Reciprocal relationships and/or values for inverse comparisons of this statement would denote [0.20, 0.34, 0.40], respectively.

The pairwise comparisons of each branch at each level of the decision hierarchy were formalized into a matrix and used to determine a vector of relative priority weights. In the present study, the algorithm of Chang (1996) is preferred as the base method for the analysis of pairwise comparison matrices using the TFNs, and also for scaling off the fuzzy numerical valuations. This method is often used in fuzzy-MCDA studies and its extent synthesis method is popular in the field of decision support system. For a comprehensive description of fuzzy sets theory and mathematical transformations from the fuzzy results to crisp definitions, we direct the reader to the excellent tutorial by Kulak and Kahraman (2005).

For each matrix, the approach requires consistency to be checked to detect possible errors in judgements. In case of inconsistency in the decision matrix (generally no more than a threshold of 0.10) questionnaires were returned to the decision-committee to reappraise their preferences until the value of consistency ratio was acceptable. In a group-MCDA context, individual preferences must be combined in some way to obtain group preferences. To do so, once the preceding questionnaires completed the individual judgements in the form of weights for decision attributes and road branches were combined. We used a geometric mean to unite judgements of several experts (Saaty 1980). We, therefore, compute relative priority weights by some kind of decision rule for the decision attributes (i.e., criteria/subcriteria and factors) and the road branches under each of attribute separately.

3.1.5. Determining environmental coefficients

The relative priority weights for the decision attributes and the road branches were multiplied and then aggregated using an additive function that resulted in final or global weights for all road branches as described in Eq. 1. Those road branches with a higher global weight will, therefore, carry a greater magnitude to cause environmental damage.

$$w_l = \sum_{j=1}^{m} \tilde{t}_j \tilde{r}_{lj} \qquad \forall i \in n \qquad (1)$$

where w_l is the final priority weight of the l^{th} road branch, $\tilde{t}_j$ is relative fuzzy weight of the j^{th} criterion (j = 1, 2… m) against the l^{th} road branch (l = 1,2… n) in the normalized fuzzy decision matrix, and $\tilde{r}_{lj}$ represents relative fuzzy weight of the l^{th} road branch against the j^{th} criterion.

Intuitively, a solution to the MCDA can be represented as a vector of priority weights for all road branches $W = (w_1, w_2, \dots, w_l)$, where w_l is the final weight or so-called *environmental coefficient* to each branch of the road network as a proxy of environmental impacts. The entire MCDA approach above allows for weighting road branches to cause potential environmental harm. This means that a final priority weight for a particular branch represents the need for that branch to receive a certain type of treatment, depending on the intensity or magnitude of (w_l). More detailed discussion on the fuzzy multicriteria decision analysis and the theoretical background of this decision theory to compute weights has been presented in the excellent work by Shukla et al. (2014).

3.1.6. Weights validation

The entire MCDA is based upon intuitively subjective assessments provided by decision-makers and thus it may provide a consistent indication or not. Therefore, we have verified the quality of solutions provided by the MCDA model from a numerical perspective. Shannon's entropy method was adapted to objectively derive attribute weights against misjudgments (Shannon and Weaver, 1963). In doing so, we want to ensure that that attributes (i.e., criteria, subcriteria and factors) with the highest priority weight, within each cluster, are not selected by chance. Using entropy, the weight assigned to a decision attribute is directly related to the average level of information or uncertainty inherent in the possible results. A low value of the entropy index corresponds to an element with a higher weight within its cluster, and therefore, a greater discriminatory power in the decision-making process.

The pairwise comparison matrices, obtained in the first step of the MCDA process, were the main source of data used for this validation analysis. The analysis is started with the standardizing decision attributes in order to eliminate anomalies as (Eq. 11). Variabilities or disorders in the relative weight of decision attributes to a certain extent within items of a cluster or the whole cluster are interpreted as anomalies. The next step was to determine the levels of anomaly and/or uncertainty for each item within a cluster through the entire decision hierarchy as Eqs.12 and 13.

Indices

j	index for decision criteria; $j = 1, 2\ldots m$
i, h	index for road branches; $i,h = 1,2\ldots n$

Parameters

x_{ij}	the individual preference or relative importance value assigned to the j^{th} criterion against the i^{th} road branch. This set of parameter obtained from pairwise comparison matrices, as the first step of the group-MCDA process
k	a constant value between 0 and 1
log	the default log algorithm is $\log_2$

Decision variables

E_j	the entropy value for decision criterion j
w_j	the uncertainty rate for decision criterion j
p_{ij}	the probability value for each entry in the decision matrix

$$p_{ij} = \frac{x_{ij}}{\sum_{h \in m} x_{hj}} \qquad \forall i \in n, j \in m \qquad (11)$$

$$E_j = -k\left(\sum_{i \in n} p_{ij} \log(p_{ij})\right) \qquad \forall j \in m \qquad (12)$$

$$w_j = \frac{1 - E_j}{\sum_{j \in m} (1 - E_j)} \qquad \forall i \in n \qquad (13)$$

The outcome of the entropy method is a subset of attributes (i.e., criteria, subcriteria and factors) that can potentially guide decisions about the frequency of rehabilitation treatments without including subjective expert opinions. This subset is called risk-assessment attributes.

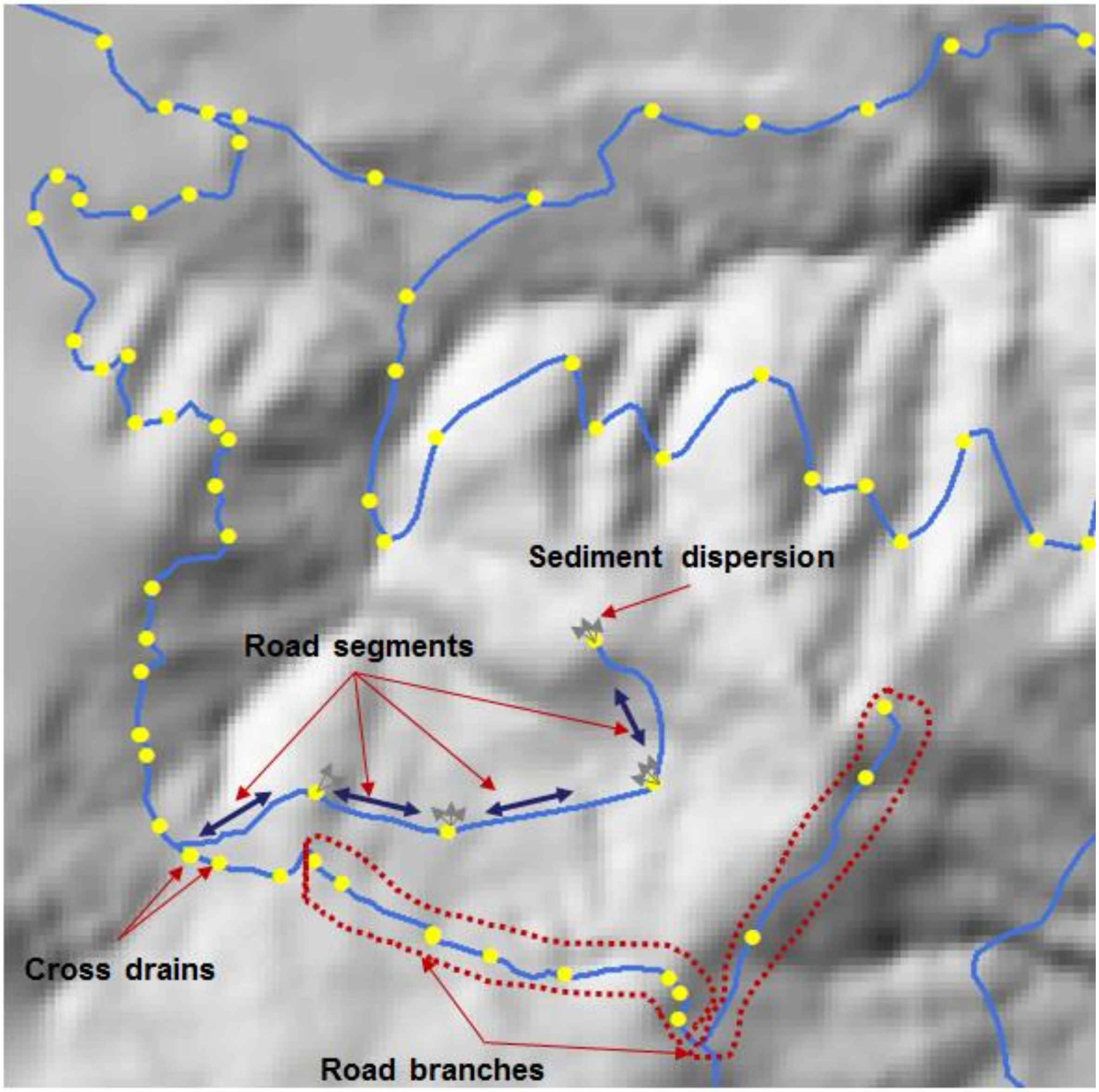
As briefly mentioned, solutions of the group-MCDA model are operationally viable. This can be interpreted to mean that MCDA techniques are likely able to generate *feasible* or (*near*) optimal solutions by analyzing massive information from a variety of aspects. In addition, they are insufficient themselves to guarantee *optimal solutions* or generate plans periodically on a rolling horizontal basis as linear programming models can do. A similar criticism had already been made on the EMDS decision-support developed by Reynolds et al (2003) for analyzing road networks subject to environmental impacts using expert knowledge. To fill this gap, the present study used the concept of sharing database between two models. To do so, we used the vector of environmental coefficients, as the final outcomes of the MCDA process, to weight environmental risks to each road branch. These weights are therefore combined with the cost of repair treatments to allocate an appropriate treatment for various segments of the road network (see sub-section 3.2). This method is similar to that of Thompson and Sessions (2008), who assigned a hazard rating to weight environmental damage to each segment of decommissioned roads.

3.2. Optimization model

3.2.1. Mathematical model development

In this section, we present a generic integer programming (IP) model aimed at minimizing the total road repair cost, subject to resource limitations and the operations connectivity specified by the constraints. The model below falls into the category of spatially resource allocation problems for making decisions on road rehabilitation treatments at the operational planning level. To create a more challenging problem with opportunities for optimization, we assume the actual decision units (road segments instead of road branches) to properly allocate repair treatments. From this point on, we used the notion of road segment as the smallest spatial unit in which a particular road branch was supposed to be made up of a set of aggregated segments. Figure 4 illustrates part of the studied transportation road network on a shaded relief model to account for differences between road segments and road branches. It exemplifies a network with several road branches to which each branch consists of a sequence of road segments.

[Figure 4]. A part of the studied transportation road network on a shaded relief model. Blue lines represent road segments; irregular shapes indicate road branch, which made from a sequence of road segments; gray arrows indicate directions of sediment flow along roadside ditch; yellow dots specify cross drains through the entire road network


Sediment dispersion
Road segments
Cross drains
Road branches

Indices and Sets

T	the set of planning periods
L	the set of road segments

Decision variables

z_{lt}	1 if road segment *l* received routine maintenance treatment in period *t*, 0 otherwise
y_{lt}	1 if road segment *l* received periodic upgrading treatment in period *t*, 0 otherwise

Parameters

h_l	the length of road segment *l*
c_l^m	the unit cost of routine maintenance ($\$\,\text{km}^{-1}$) for road segment *l*
c_l^u	the unit cost of periodic upgrading ($\$\,\text{km}^{-1}$) for road segment *l*
B_t	the budget target available in period *t* for rehabilitation works (i.e., maintenance and upgrading)
α	discount rate

The mathematical formulation of the model is as follows:

$$\text{Minimize } k_1 = \sum_{t \in T} e^{-\alpha(t-1)} \left[\sum_{l \in L} c_l^m h_l z_{lt} + \sum_{l \in L} c_l^u h_l y_{lt} \right] \qquad (2)$$

Subject to the following constraints:

$$\sum_{t \in T} z_{lt} = 1 \qquad \forall l \in L \qquad (3)$$

$$\sum_{t \in T} y_{lt} \le 1 \qquad \forall l \in L \qquad (4)$$

$$\sum_{l \in L} c_l^m z_{lt} + \sum_{l \in L} c_l^u y_{lt} \le B_t \qquad \forall t \in T \qquad (5)$$

$$y_{lt} \le \sum_{t' \le t} y_{l't'} \qquad \forall l \in L, l' \subset l, \ \forall t \in T \qquad (6)$$

$$z_{lt} \le y_{lt+3} \qquad \forall l \in L, \ \forall t \in T \mid t \ge 3 \qquad (7)$$

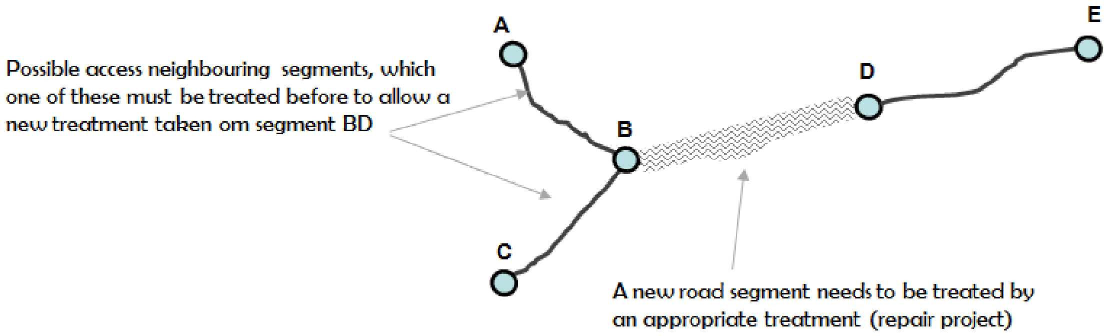
$$z_{lt}, y_{lt} \in \{0,1\} \qquad \forall t \in T, \ \forall l \in L \qquad (8)$$

The objective function (Eq. 2) minimizes the discounted costs of repair actions over the planning horizon, assuming that the first period ($\mathrm{t} = 1$) is the current period. In the case study, the planning horizon was set at 10-year, divided into ten 1-yr periods. The reason for choosing this horizon was to provide detailed information on the timing and location of various rehabilitation treatments on a yearly basis.

Constraint set 3 ensures that each road segment shall have received exactly one maintenance treatment. Constraint set 4 forces the model to choose road upgrading treatment at most once. The total repair cost must reflect budget targets for each period as specified in constraint set 5. Constraint sets 6 and 7 are project-to-road trigger constraints, similar to those first introduced by Kirby et al. (1986) and Guignard et al. (1998). These constraints are used because they provide a tighter formulation to integer or mixed-integer problems in such a way as to avoid the generation of isolated links (i.e., uneconomical integer-feasible solutions) in the resulting network (Weintraub et al. 2000; Andalaft et al. 2003). The main intention of defining this set of constraints, in the current formulation, ensures connectivity of treatment projects (i.e., upgrading) across the road network. This can be interpreted to mean that a segment l can be upgraded in t only if another segment that gives access to l ($\acute{l}$ in access l) was upgraded in any period before t ($\acute{t} \leq t$). Set 6 describes connectivity of upgrade treatments among adjacent segments. Constraint set 7 spatially links two decision variables and guarantees the continuity of various repair treatments (maintenance and upgrading) in a sequence of three years. This means that if a segment has maintained in the first-year of the maintenance cycle, upgrading of that segment will start with a delay of three-year maintenance cycle. Finally, sets 7 and 8 declare the decision variables restrictions.

A schematic representation of project-to-road triggers is given in Figure 5. This figure simply implies that the target road segment BD should not receive a treatment project in any periods unless one of its access neighboring segments, i.e., AB or CB has received a treatment in advance. In this way, the network optimization problem is self-adjusting based on the selection of continuous repair projects and avoids the forming of isolated repair projects across the network. This will affect the size of the search algorithm and ensure that optimal solutions are identified quickly (Guignard et al. 1998).

[Figure 5]. Illustration of project-to-road triggers constraints



3.2.2. Append environmental coefficients

Apparently, the best possible solution would seem to be assigning light treatments of cheap operating costs (maintenance treatments) to a large part of the road network accompanied by a small proportion of heavy treatments of expensive costs (upgrading treatments), which minimize costs, but may not include environmental impacts and/or priority weights in this analysis. In order to account for this, we add the priority weight of environmental impacts to equation 2. Thus, the objective function problem (Eq.2) is reformulated as (Eq.9) by multiplying the environmental coefficient for a particular road branch (w_l), as the final outcomes of MCDA process. It is thus given by:

$$\text{Minimize } k_2 = \sum_{t \in T} e^{-\alpha(t-1)} \left[\left(\sum_{l \in L} c_l^m h_l z_{lt} + \sum_{l \in L} c_l^u h_l y_{lt} \right) w_l \right] \tag{9}$$

With the increase in the magnitude of w_l , the road branch carries a greater weight to cause environmental damage, and hence a higher priority weight to be rehabilitated in the earliest possible time with an appropriate treatment. The resulting weighted-objective function (Eq. 9) minimizes total costs of repair actions, considering two costs: the present cost of routine maintenance (the first term) and the present cost of periodic upgrading (the second term), which multiplied by the extent of negative environmental impacts.

We should further recall that, through the MCDA phase, the vector of w_l defines environmental coefficients corresponding to each road branch (i.e., the coarse decision unit, which includes a set of aggregated segments). We, therefore, needed to compute this weight for all segments (i.e., the fine decision unit, which emanates from a particular road branch) in a suitable way consistent with the preceding assumptions of the optimization model. To do so, we extended the normalised vector of environmental coefficients as the number of road segments (i.e., 194 weights instead of 21 weights). This means that, a global priority weight belonging to a particular road branch can be distributed equally among segments emanating from that branch. This is the necessary step accomplished to assign priority weights to road segments instead of using aggregated forms of road length in the way of numerical analyses.

This information would seem sufficient to generate an optimal solution to the actual problem at the segment level, yet it is loose, in the sense that we do not know which types of repair treatments (maintenance or upgrading) should receive this priority weight? To address this, we partitioned the environmental coefficient 'w_l ' into $w_1 > 0$ for road maintenance treatment and $w_2 > 0$ for road upgrading treatment such that $w_{l1} + w_{l2} = 1$.

The magnitude of environmental coefficients depends on physical status of the road length for various repair treatments, and therefore equal combinations of that may or may not be realistic. To do so, we implemented combinations of weight to road repair costs to generate an efficient tradeoff curves between total cost and the negative environmental risk; due to the selection of various repair treatments. For example, a small change in the magnitude of w_i enforces the model to precede light treatments of inexpensive operating costs or maintenance, given that the road segment already carried a lower weighting value for environmental impact. A higher weighting value, conversely, compels the model to forego heavy treatments of expensive costs or upgrading, if the segment has not received any actions before.

The tradeoff curve is therefore generated by selecting an optimal treatment for each segment of the road network (maintenance which is inexpensive, but need to be done intensively, or upgrading which is expensive, but can be done infrequently), while simultaneously considering the magnitude of negative environmental impacts and the cost of repair operations. This allows for more accurate operational road repair plan to be made, through combining both objective and subjective modeling approaches. It is thus revised the objective function (Eq. 9) as follows:

$$\text{Minimize } k_3 = \sum_{t \in T} e^{-\alpha(t-1)} \left[\sum_{l \in L} c_l^m h_l z_{lt} w_{l1} + \sum_{l \in L} c_l^u h_l y_{lt} w_{l2} \right] \qquad (10)$$

The resulting objective function (Eq. 10) can be solved several times under different weighting combinations to generate a range of non-inferior solutions, in which one repair treatment can be generated only by sacrificing the other treatment.

3.2.3. Model solving and sensitivity analysis

All computations pertain to the optimization model were conducted on a machine with 2.90 GHz, an Intel core i7, and 8 GB of memory. The mathematical model was implemented using ILOG AIMMS with CPLEX 12.8 solver. The actual model has 3,240 constraints, 6,440 integer variables, and 23,517 nonzero variables (i.e., how many coefficients of the matrix are nonnegative values). The model is not computationally intensive solving. A typical runtime for one solution using this formulation is approximately 3.5 s. Given the number of decision variables, this seems like reasonable performance for a problem of this magnitude. We designed a number of scenarios by modifying the available budget to gain a sense of how well the model performs in achieving optimality. For each scenario, eight non-inferior solutions for environmental impacts were generated (one base value, and seven changed values) by varying weighs w_{l1} and w_{l2}, respectively, for maintenance and upgrading (Table 6). To gain good approximation of the tradeoffs curve, combinations of static weightings extreme between $1-\varepsilon$ and ε, were put into simulations.

Table 6. Weightings extreme for the repair treatments

Weightings extreme (E)	Combination of weighting value	
	w_{l1}	w_{l2}
0 and/or base level	N/A	N/A
1	0.00001	0.999999
2	0.05	0.95
3	0.20	0.80
4	0.50	0.50
5	0.80	0.20
6	0.95	0.05
7	0.999999	0.00001

3.3. Case study

To validate the model developed and illustrate its effectiveness in providing meaningful solutions, we applied it to a realistic setting covered by 289 km of gravel-surfaced roads (e.g., used for moderate traffic load and lifespan). These off-road transportation networks are connected to a 19 km of public road (e.g., intended for a high traffic load a long service life) in the central highland of the Hyrcanian forests in northern Iran. The public road has excluded from the current analysis. Roadbeds were built on a 50-cm-thick of gravel ballast with a constant width of 4-m and an average gradient of 8%. The current network contains 322 segments, which are intervening stretches of the road that located among one or several culverts, consist of roadbed, cutbank and fillslope (fine spatial decision units). These segments operationally belong to 21 road branches, e.g., roads connecting several cutting blocks of variable lengths (coarse spatial decision units). The road segments are different in their repair regimes, traffic levels, drainage systems, geometric attributes, e.g., length, curvature geometry, construction time and road gradient. Table 3 presents a brief description of the case study.

Table 3. General information of the study area

Aspect	Entire road network
Soil textures	Clay-loam-sand and silty-clay-loam
Stand structures	Mixed stands (e.g., beech-oak, hornbeam, *etc.*)
Logging history	Semi-mechanized- animal logging
Drainage systems	Crowned, out-slope and in-sloped ditches
Road surface material	A range of mixed river gravel ballast with crushed sandstone
Elevation A.S.L. (m)	150 - 2,200
Precipitations (mm)	645 - 671
Natural hillslopes (%)	24.00
Culverts spacing (m)	~ 150 - 400
Road lifespan (yr)	≥ 5 - 10
Traffic levels (truck volume per day)	10 - 50
Road gradient (%)	3 - 10
Lane width (m)	3.50
Shoulder width (m)	1.00

Maintenance regime (yr)	3 - 4
Designed road width (m)	5.50
Average distance to stream (m)	80 0– 2,500
Cutslope height (m)	2.00

The region lies geographically between 36° 25'N and 36° 35'N latitudes and 51° 36'E and 51° 46'E longitudes in northern Iran, has variable topography with an average hillslope gradient of 35%, significant amount of precipitation (on averaged about 1,308 mm yr^{-1} with very large inter-annual variability) with an average humidity of 82%. The area of concern for this study included 400 km^2. Over 85% of the study area is covered with dense broadleaved forests, largely managed for timber production. Road mass failures and the potential for landslides within the study area are known to be low. In addition to commercial utilization, other forest management objectives are conservation, rehabilitation, rural development, research and education. Harvesting operations are carried out using single-tree selection system in the context of close-to-natural silviculture, which necessitates a high density of the road network. There are 246 harvest units ranging from 50 to 90 ha sometimes up to 120 ha in size. The current road networks serviced more than 1,000 m^3 of roundwood to multitude forest companies on a yearly basis by short log trucks and dump trucks.

The cost of road rehabilitation depends on the length of segment, the distance to a nearby quarry or pit, and the physical condition of road pavement. For the case study, we assumed US$1,742 per km for maintenance, and US$5,225 per km for upgrading. The cost data are calibrated according to current standard guidelines for gravel-surfaced roads in mountainous forests of Iran. The basic annual discount rate is assumed to be 4%. There is also no exact value on the budget constraints for road repair treatments, we, thereby, assume a US$1.2E+5 as the required budget targets for each planning period. It should be noted that this level of budget was estimated exogenously from a road repair operation project executed for the last ten years. A complete description of input data used in this study is presented in Appendix 1.

4. Computational experiments

4.1. Group-MCDA

Given 35 decision attributes along with 21 road branches and five experts, a total of 4,025 pairwise comparisons were carried out. This level of analysis was impossiblemvia ordinary decision-making tools, such as Expert Choice software. We, therefore, developed a spreadsheet calculator within the Microsoft Excel to consider such a large number of analyses. Table 4 shows the relative priority weights (i.e., fuzziness numerical values) for each of the attribute subject to dependency relationships in each branch at each level of the decision hierarchy. The inconsistency ratio was less than 0.1 and all pairwise comparisons were accepted as consistent. Some influences can be useful for further studies. For example, among the assumed criteria for the first level, ‘terrestrial impact’ was the most important criterion (0.448); followed by ‘erosion and sediment risk’ (0.405), whereas direct impact to ‘aquatic habitats’ was considered less important (0.147) with respect to the overall goal. The highest relative weight (0.161) was related to the subcriterion ‘landslide susceptibility’ among all the subcriteria descended from the criterion the ‘terrestrial impact’ at the upper level. The subcriterion ‘road design characteristics’ had the highest relative weight (0.154) among all subcriteria-related to the criterion ‘erosion & sediment risk’. The factor ‘types of tree species’ was the most important (0.369) within assumed factors describing the subcriterion ‘vegetative cover’. The factor ‘quality of pavement’ had the highest relative weight (0.159) corresponds to ‘road design characteristics’ at the subcriterion level. The subcriterion ‘traveledway conditions’ (e.g., width, vehicle way, *etc*.) had the highest relative weight (0.557) with respect to the criterion ‘aquatic impact’. Likewise, ‘cross-drain conditions and status of ‘road surface aggregate’ were considered evenly as the most important factors (0.211) describing ‘traveledaway conditions’ at the third level. Relative priority weights for other components of the decision-hierarchy are specified in Table 4.

Table 4. Deriving relative priority weights for the hierarchical decision model

Decision attributes			Relative priority weight
Criteria (level 1)	Subcriteria(*SC*) (level 2)	Factors(*F*) (level 3)	
Terrestrial impact (0.448)	T-SC1. soil depth		0.148
	T-SC2. drainage system		0.153
	T-SC3. geologic factors (rock type)		0.141
	T-SC4. road lifespan		0.137
	T-SC5. landslide susceptibility		0.161
	T-SC6. elevation A.S.L.		0.118
	T-SC7. natural spring		0.138
Erosion & Sediment risk (0.405)	E-SC1. soil texture		0.154
	E-SC2. **V**egetative cover (0.125)	V-F.a. types of tree species	0.369
		V-F.b. tree density	0.331
		V-F.c. canopy cover	0.300
	E-SC3. road lifespan		0.149
	E-SC4. logging history		0.150
	E-SC5. slope steepness		0.144
	E-SC6. elevation A.S.L.		0.121
	E-SC7. Road **D**esign characteristics (0.155)	D-F.a. road gradient	0.153
		D-F.b. quality of pavement	0.159
		D-F.c. right-of-way width	0.114
		D-F.d. biotechnical practices	0.140
		D-F.e. culverts spacing	0.148
		D-F.f. steepness of cut/fill	0.143
		D-F.g. rock hardness	0.140
Aquatic impact (0.147)	A-SC1. **T**raveledway conditions (0.557)	T.a**.** status of road surface aggregate	0.211
		T.b. quality of subgrade	0.193
		T.c. traffic flows	0.180
		T.d. apron drainage	0.203
		T.e. cross-drain conditions	0.211
	A-SC2. hillslope towards the river		0.222
	A-SC3. road distance to stream		0.222

The first or sometimes the second letter of a phrase is labeled as a directive sign to divide the decision element(s) from the existing level to another.

Figure 6 indicates the normalized global priority weights and/or the environmental coefficients in percentage resulted from combining relative priority weights for the attributes associated with all road branches. The environmental coefficient varied from 0.02 (branch with low impact) to 0.08 (branch with high impact), depending on the extent of the global weight. A higher weighting value for a road branch indicates a greater priority or potential risk of causing environmental damage, thereby a higher demand of that branch to be rehabilitated. This figure implies that all road branches can be narrowed down to three priority zones. Roads with a high need for rehabilitation treatment (zone 1: 33% of all branches), which represent a higher risk of environmental impacts, and should therefore be considered as the highest priority compared to those presenting the lowest level of risk(zone 3:24% of all branches). Between these extremes, there are branches with a moderate level of risk (zone 2:43% of all branches), which indicate that the rehabilitation treatments for these branches can vary, either at an inferior standard or at a superior standard. As can be seen the outcomes of the MCDA guided decisions, which part of the road network needs to be repaired, but it is impossible to determine the regime and schedule of repair treatments during the planning horizon.

[Figure 6]. Vector of normalized environmental weight values for all studied road branches

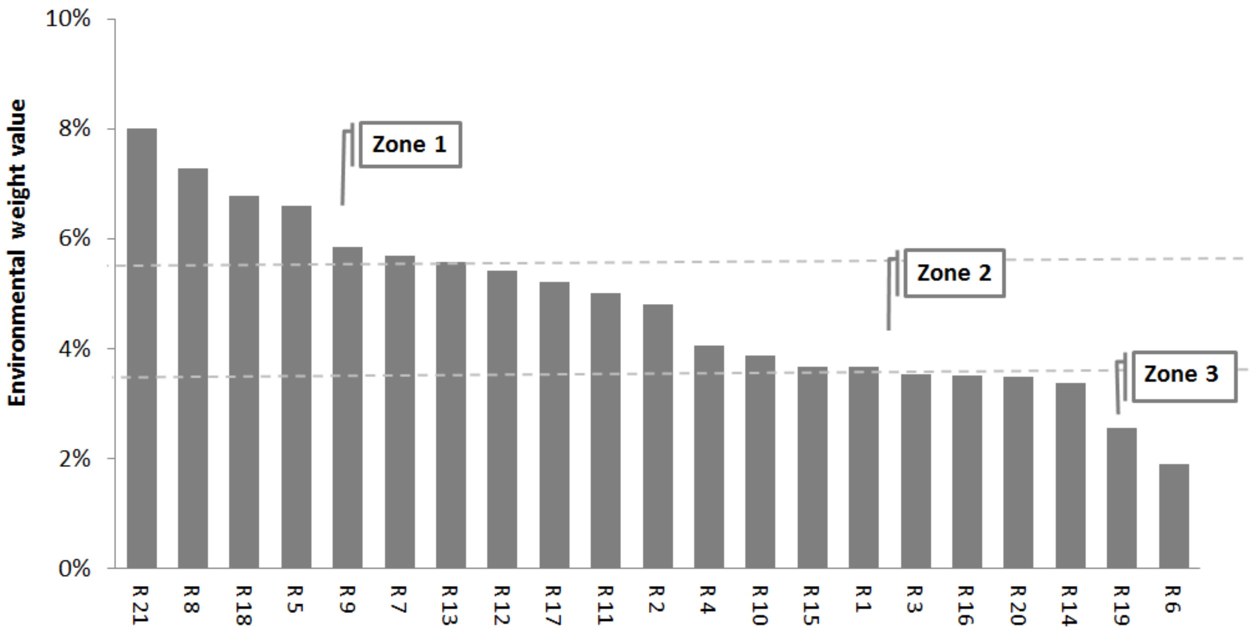


Table 5 shows the result of weights validation by the entropy approach. Each item in this list has a higher weight value among all the items in its own cluster. As can be seen, six of the eight attributes were distinguished from the pool of decision attributes (refers to Table 4) in the two approaches. This demonstrates that these attributes have the lowest entropy value and therefore greater discriminatory power within its own cluster. They can be considered as significant site-specific factors for the preliminary evaluation of road networks subjected to repair treatments. This subset of decision attributes is, henceforth, called the *risk-assessment attributes* for consistency.

Table 5. Risk-assessment attributes used for the visual assessment of the road network

MCDA model		Entropy verification model	
Decision element	AHP's relative priority weight	Decision element	Entropy's objective weight
Traveledway conditions	0.557	**Traveledway conditions**	0.076
Landslide susceptibility	0.161	**Landslide susceptibility**	0.064
Types of tree species	**0.369**	**Types of tree species**	0.050
Quality of pavement layers	**0.159**	**Quality of pavement layers**	0.050
Status of road surface aggregate	**0.211**	**Status of road surface aggregate**	0.050
Terrestrial impact	**0.448**	**Terrestrial impact**	0.028
Cross-drain conditions	**0.211**	Quality of subgrade layers	0.051
Road design characteristics	**0.155**	Drainage system	0.024
		Biotechnical practices	0.055

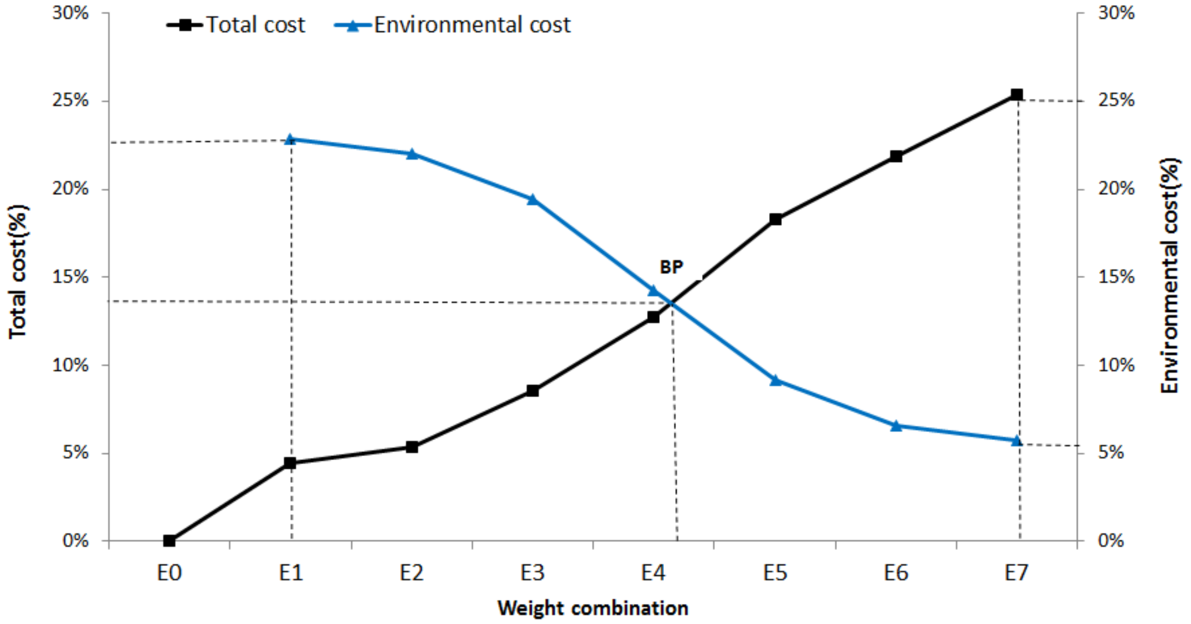
- An identical set of decision elements is marked in dark font using multi-criteria decision analysis (MCDA), and entropy models. Disparate elements are shown in standard font

4.2. Optimization model

The tradeoffs curve then quantifies the selection of best repair treatments for each segment according to the magnitude of environmental impacts. Figure 7 illustrates the usefulness of the optimization model in decision analysis in which the available budget target is limited to \$1.2E+5 with a discount rate of 4%.

Since there is no costing value to account for environmental impacts, rather we used the percentage of changes in total cost due to the involving the effect of environmental impacts in the selection of repair treatment. The percentage was calculated based on actual costs excluding the cost of environmental impacts. This assumption was reasonable so that the total costs would increase with involving constraints related to environmental impacts. The base level of weight extreme (E_0) used actual costs excluding the cost of environmental impacts, representing the status quo management, and the least-cost scenario for repair treatments in the studied area. Since this scenario has not given any priority weights to repair treatments, it resulted in the lowest cost of US\$6.7E+6 for the entire network. At this level, maintaining the current state of the road is not preferred, because the model allocates a large proportion of maintenance treatments with a few km upgrading treatments (21% of the total length) to the road network. The total cost has an increasing trend with involving weights for the environmental impact. By examining the tradeoffs curve, before the fourth extreme (E_4), we can see a strong downward trend in environmental impacts with a slow and steady upward trend in the total cost. Road segments with a higher weight value, i.e., segments must be rehabilitated instantly, lend themselves to upgrading, while segments with a lower weight value can be treated with maintenance treatments. Because the higher total costs are always compensate by selecting a large proportion of the expensive treatment, i.e., road upgrading, which will reduce the total cost. At the other extreme (E_7), spending of US$4.9E+7 for road repair treatments drops the total cost of environmental impacts to the minimum level of US$4.3E+6. This suggests that, in this worst case, the model becomes progressively less desirable by aggregating upgrading treatments and forces them to be practiced in shorter periods (i.e., periods six and seven) without projecting them onto other periods. The fourth extreme (E_4) seems to provide the most efficient level, since total cost curve is crossed by the environmental curve. This point is termed a breakpoint (BP), and identifies a solution allowing significant reduction in environmental impacts with a very small increase in total cost. This level of the weighting shows strong payoff in the total cost, which allows a considerable decrease in the weighting values for the negative environmental impact. After this level, there are very few additional benefits from reducing environmental impacts, as reducing environmental costs has resulted in in an associated cost increase of approximately 25% compared to the status quo management.

[Figure 7]. Tradeoff curve for the total repair cost versus environmental costs corresponds to various weightings extreme



More specifically, at the extremes E_1 through E_3, the model assigns all or most of the road segments an appropriate treatment in order to take advantage of the additional benefit of the allocation of rehabilitation treatments by reducing environmental costs in a range of 23% to 14%, respectively. At the next extreme (E_4), as the likelihood that upgrading and maintenance treatments are in appropriate balance whereas after this extreme (E_6 through E_7) the model is willing to pay a higher cost, ranges from 18% to 25% over the base cost, using more upgrade than maintenance treatments, to reduce the total cost.

Figure 8 illustrates an example of allocation of repair schedules for the existing network generated by the proposed decision approach, in which the scale on both vertical axes has shown to clarify details. Maintenance treatments were dominant at the beginning of period, while they gradually superseded with upgrading treatments started from the middle of the period towards the end of period. These results can be translated into a uniform distribution of available budget while attaining lower costing values on the one hand, and avoid the congestion of repair treatments in a particular period on the other hand.

[Figure 8]. Distribution of the available budget for maintenance and upgrading treatments in which weighting level for the repair treatments sets to (E_4= 0.5, 0.5)

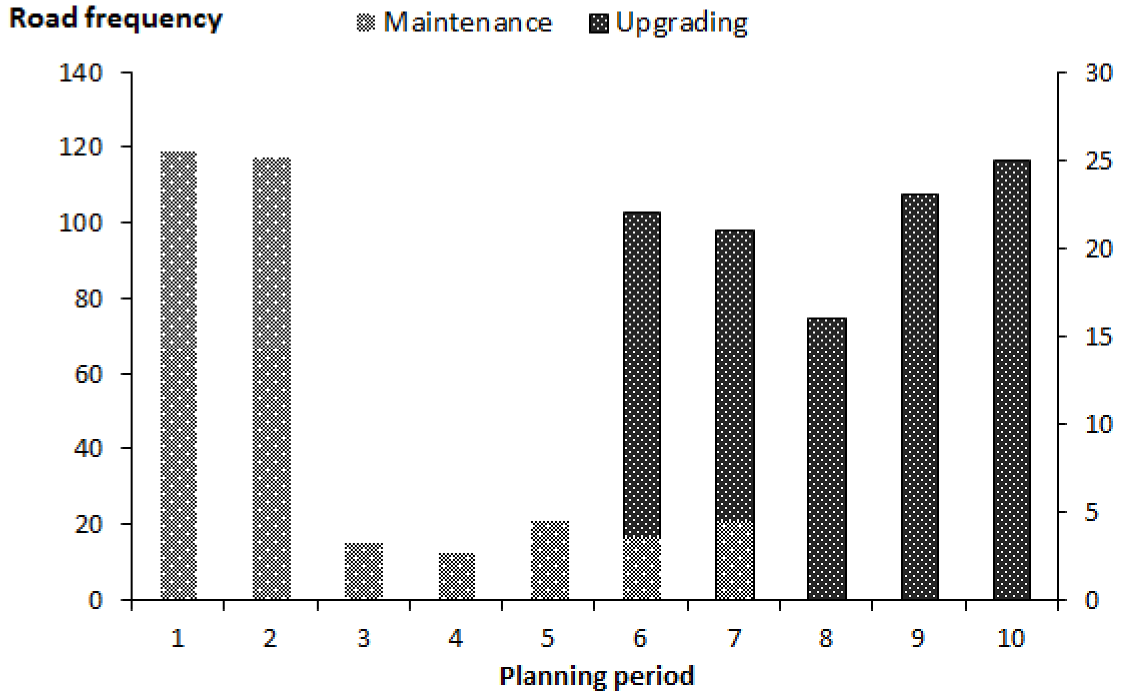


Table 7 shows the total cost of rehabilitation and the associated road lengths for maintenance and upgrading treatments subject to different levels of budgetary constraints over a range of ±5% of the base value. Two combinations of weights were analyzed, among others: i) status quo management scenario to which no priority weights was assigned to the selection of repair treatments (E_0), and ii) optimal management scenario to which a priority of 0.5 was considered for both maintenance and upgrading (E_4), as the cost-effective extreme over the tradeoff curves. Total road length in the study area is 289 km. Since the status quo management scenario has no associated environmental cost, it results in the lowest repair costs with the minimum length of roads to be repaired.

Table 7. Actual rehabilitation costs and road length compare to base-case (status quo management)

Scenario	Cost component	Budget level (US$)				
		110,000	115,000	**120,000**	125,000	130,000
Status quo management (E_0)	Maintenance cost	3,752,942	3,737,559	3,722,181	3,706,801	3,691,423
	Upgrading costs	3,451,900	3,204,033	2,956,161	2,708,292	2,460,420
	Total operation cost	7,204,842	6,941,592	6,678,342	6,415,092	6,151,843
	Total length of maintenance	208.70	217.43	228.22	235.50	245.82
	Total length of upgrading	80.20	71.47	60.68	53.40	43.08
Optimal management (E_4)	Maintenance cost	8,267,967	7,616,700	6,905,963	6,478,354	5,971,802
	Upgrading costs	4,513,186	4,165,049	3,922,975	3,430,396	3,037,389
	Total operation cost	12,781,153	11,781,748	10,828,938	9,908,750	9,009,191
	Total length of maintenance	177.74	184.66	193.89	200.77	210.04
	Total length of upgrading	111.26	104.34	95.11	88.23	78.96

- Maximum solution time was bided to 3,600 seconds with a default value for optimality gap (i.e., 10^{-5}), the budget target assumes to be US$1.2E+5 in which the weighting factor for the optimization model sets to ($E_4 = 0.5$). All costs and lengths of treatments are presented in US$ and km, respectively

The total repair costs do not vary much (10% at most) among different levels of budget constraints. The lowest costing value is obtained when the available resource has been set to US$ 130,000 for the entire network. The same results were observed for the optimal management scenario. This means that the lower costing value is possible (by about 17%), if the available budget is increased by just over 10% of the budget target. Since the solution of the optimal management scenario has penalty for the environmental cost, it resulted in a cost value of 38% higher, on average, compared to the status quo management scenario. By looking at road lengths it can, however, be deducted that 79% of the road segments are lent themselves to maintenance with the allocation of 21% to upgrading when the status quo management scenario is implemented. These proportions increased to 67% and 33%, respectively, for maintenance and upgrading, using an optimal management scenario.

Figure 9 shows the layout of repair treatments for the status quo management scenario (E_0) and the optimal management scenario (E_4) generated by the integrated approach. The status quo management scenario (i.e., an alternative without considering environmental impact) shows enormous isolation repair treatments across the network, which mainly targeted shorter segments to reduce the total cost of operations. By comparing this solution, it can easily observe that, the solution obtained by the optimization management scenario has more aggregations or continuity of treatments (i.e., less swapping of repair actions on additional segments and targeting segment with longer lengths) compared to the solution of the status quo management scenario.

5. Discussion

The annual and periodic costs of operational road rehabilitation often constitute a large proportion of the forest management cost, particularly in mountainous regions involving highly variable and steep terrain where higher operating costs are coupled with growing harmful environment impacts. The decision-making approach presented here demonstrates a generic framework. It is accompanied by a more comprehensive decision-making model that might yield opportunities to increase efficiency of forest road management with less environmental impact.

We used expert knowledge through multi-criteria decision analysis to determine potential environmental risks associated with the road network, and to prioritize road segments that might require special treatments. This analysis also provides weights for harmful environmental impacts combined with the cost of rehabilitation treatments used to support existing operational road decisions on a rolling horizontal way.

The expert opinions analysis asserted that a large part of the existing roads (76%: 33% of roads in zone 1 with 43% of roads in zone 2) must be prioritized to receive rehabilitation treatments in the earliest possible time. An implication of this observation is that the road under study has greater potential to cause negative environmental impacts and must therefore be rehabilitated as intended for logistic purposes. The risk-assessment attributes are a generic checklist, potentially could include the full suite of road experts to assess existing road conditions and determine perceptions about which road attributes are most important in deciding the frequency of repair treatments before monetary investments.

Without considering numerical analysis, it can be stated that risk-assessment attributes asserted three broad classes of decision variables to address roads transportation for a variety of potential and actual environmental risks. These include: i) attributes-related to road design standards (e.g., traveledway conditions, quality of paved layers, condition of aggregate, quality of subgrade layers, and the condition of drainage systems), ii) external factors contributed to the risk of landslide and the impact of these factors on the existing road network, and iii) botanical attributes (e.g., types of tree species and biotechnological practices).

Regular maintenance of road design standards in a condition suitable for travel can reduce the risk of soil erosion and sediment yield (Luce and Black, 2001). Moreover, unsuitable materials used for the armoring road surfaces, i.e., pavement and subgrade layers, and unprotected drainage systems can aggravate the challenges mentioned above. According to the result of MCDA, botanical attributes are considered as important safeguards to reduce negative impacts caused by forest roads. This can be interpreted to mean that vegetated cutbanks and fillslopes can reduce the intensity of surface flows and trap sediment yields, especially during intense or prolonged precipitation in uplands and middle mountains. However, the controlling effect of ground cover can vary depending on the types of tree species, density and the canopy cover (Lenka et al. 2017). Luo et al. (2020) found that surface runoff and sediment generation were significantly correlated with the different types of vegetation. Mixed hardwood and shrub forests were the best types of surface runoff control, due to their high surface coverage compared to evergreens, especially during periods of heavy precipitation.

It is noteworthy that the attributes discussed above (i.e., risk-assessment attributes) are technically relevant to each other. Considering these along with other observations from field inventories allows road technicians to properly evaluate environmental impacts caused by the road system, to identify road sections with a higher level of risk, and discerns minor deficiencies before turning to serious problems. It also helps to suggest possible preventions, and therefore to minimize rehabilitation costs induced by the allocation of segments that are too early or too late in their developments.

Weaver and Hagans (2007) pointed out that preliminary evaluations of the existing road are highly required before taking management policies. The approach demonstrates here can be easily generalized, and applied to different road scenarios in other regions. Although model tailoring is necessary for some site-specific attributes with different levels of risk, depending on the physical conditions of site and the road users. The road managers of these forests are going to implement this decision-making approach for their annual analyzes during the next planning period.

The quality of solutions (criteria weightings) generated by the MCDA model is addressed by the entropy-based metrics. The potential implication for this method clearly resides in its impartially in deriving relative priorities for a set of criteria by excluding opinions of decision makers in the resulting analysis. The entropy analysis confirmed a 70% similarity in the output, in which six of the eight elements found by this analysis were similar to those already introduced by the MCDA model (See Table 6). A few attributes, however, were not similar in the two approaches (non-bold elements; See Table 6); this does not mean that these attributes are not relevant. It only means that considering these attributes makes the system unstable (causing a higher level of uncertainty within its cluster) and, therefore, the entropy method explicitly ignores them.

The connection of subjective modeling approach and the numerical model was the critical step, and certainly a unique contribution of this article. As noted earlier, a number of tactics have been proposed for linking these two models in various forest planning problems. We addressed this linkage using the idea of a shared database (i.e., the use of environmental coefficients, as the final output of the MCDA model), providing an effective method for conducting integrated planning analyses. The choice of obtaining weights for the environmental impacts is highly dependent on professional judgements and generally there is no formal procedure for deriving these weights. A similar idea was presented by Seely et al. (2004), who inferred that the use of a shared database is an effective mechanism to dynamically dissolve a series of complementary models involved in large-scale forest management practices.

Regular maintenance is one of the keys to reducing environmental impacts. An increase in the objective function contains environmental constraints (See Table 8) is consistent with previously reported results. Rackley and Chung (2007) reported that integrating environmental impacts into the road transport model reduced sediment delivery up to 39% at the expense of 10% increases in costs compared to the baseline scenario. As further amplification of the proposed approach, we can indicate a reasonable distribution of rehabilitation treatments across the planning horizon. This is manifested not only by observing a very reasonable shape of the tradeoffs curve, due to selecting an appropriate treatment for each road segment (See Figures 8), but also by distributing the treatments in relation to the status quo management scenario (See Figures 9).

In Iran, a general opinion is that maintenance should be intended to treat all or most of the roads at a minimum standard and cost to keep the road system serviceable. This will ensure that road design standards remain in an appropriate condition to meet all possible functions of the forest. This is, however, far from the reality, due to the continued deterioration in the expected safety and increased the risk of harmful environmental impacts caused by heavy traffic. The fact is that maintenance is an important and necessary treatment that can occur frequently in response to a low level of environmental risk related to the road system. Nonetheless, maintenance treatments on their own cannot sufficiently prevent road deterioration or minimize negative impact (Luce and Black, 1999) as upgrade treatments can do. Therefore, an effective plan must be tailored to compromise the frequency and cost of various repair treatments, extend the interval of costly treatments, and thereby minimize the overall operation cost over the planning horizon. In the current study, the input cost values for the periodic upgrade were found to be three times higher than those for routine maintenances. Therefore, we intentionally implemented a frequency of three-year upgrade cycle in the model formulation with a delay right after the last maintenance cycle. This enforces routine maintenance treatments to be happened once for each segment during the planning horizon, provided that the segment has not received any treatment. It should be noted that we also tested an intensity of two-year upgrade cycle. There have been large changes in the layout and location of repair treatments, particularly for road upgrading, suggesting that a three-year frequency was the best alternative. Besides, local road managers enlighten us on the fact that the frequency of two-year implies a short cycle for road upgrades, this strategy was therefore discarded.

The higher weighting value and/or being larger the extent of negative environmental impact indicates weak offset, which guides the optimization model becomes rather greedy in the choice and allocation of repair treatments. It is therefore strongly recommend that a road decision-maker never choose higher weighting values for the repair treatments, i.e., the right-hand side of the tradeoffs curve. This is coupled with an increase in total costs by assigning segments a high proportion of expensive treatments in order to compensate the higher environmental cost.

Therefore, a compromise of these treatments would be necessary to simultaneously reduce the total cost and the associated environmental damage. Our results indicate that the fourth extreme (E_4) of the tradeoff curves provided the most effective scenario looking at adverse environmental impacts. At this specific level, the total cost curve crosses the environmental cost curve. In addition, the repair treatments are distributed evenly across all segments throughout the planning period, reflecting a significant reduction in environmental impacts with a very small increase in total cost.

This finding is consistent with the fact that budgetary resources are often restricted at the beginning of a forest management plan, due to substantial reductions in wood sale, and also avoids investing in costly operations such as road construction or associated rehabilitation practices. Over time, the accessibility of unutilized timberlands increases. This would give planners the advantage of allocating available resources in such a way as they invest in costly treatment when the plan is fully established or there is less additional risk to the total cost.

The lack of available resource often impedes timely interventions on the road network. As indicated in the results of the optimization model, total costs were affected by the change in the amount of available budget. This result indicates that the total cost can be reduced by around 17%, only if the target budget is increased by 10% co pared to the basic budget.

In some respects, our integrated decision approach is similar to that of Reynolds et al. (2003), who proposed EMDS for environmental evaluation and planning of road repair treatments on several spatial scales. The EMDS used the knowledge-based hierarchical structure to combine spatial-based data of multiple scales using fuzzy rules to determine the degree of uncertainty in the input data. However, this model does not provide plans in a rolling horizontal manner as the current development can do. Unlike EMDS, which requires a qualified manager to work with, the approach demonstrates here is simple, transparent, and could be used by road management agencies to analyze transportation roads for the environmental risks combined with operational costs.

Beyond the desirable characteristic of this development, there are shortcomings. First, the development of questionnaires has found to be exceptionally challenging. The preprocessing step of the MCDA is, nonetheless, tedious, and tends to quickly grow complex as a number of decision attributes increases (i.e., it took almost a year to complete 4,025 pairwise comparisons). Similar criticisms have already been made by Ananda and Herath (2008) and Korosuo et al. (2011) encountered a problem, related to a large number of comparisons, in which the decision-maker simply lost his/her commitment to the task along the way. Second, the objective function does not include any spatial decisions on harvesting stands, and then the optimal solution might have a bias. In the optimization model, we enforce maintenance treatments to occur once in any road segment during the planning horizon. However, in practice, if the road connects harvesting cutblock, it is likely that this part of the road requires more frequent treatment than usual.

As previously mentioned, in these forests, the logistics decisions have been planned independently of harvesting decisions so far. Besides, due to the importance of financial considerations as the major driver of road repair decisions at the operational level, and more importantly, of recent forest management policy, careful selections of repair treatments were more of concern, for the present work, rather relating road repair decisions with traditional harvest decisions. We do believe this coincidence must be addressed in the future decision framework, if the model is used as a full package for an operational planning. This issue remains as an interesting scope for improvement.

It is important to note that, however, the entire decision approach is not only designed to generate the best optimal solution. Rather, a model of this type should be considered as one of many possibilities to support spatially road operational decisions, in which the manager's goal is to select an optimal level of repair schedule and repair regime required, considering monetary and non-monetary terms, thereby providing valuable insight to road managers.

Conclusions

This study addresses an important element of forest management that corresponds to the operational plans for repair treatments of the existing road network. First, it demonstrates a cost-effective approach to support spatial decisions in order to obtain environmental information and establish road rehabilitation plans in a subjective manner of group-decision making. The approach then incorporates this information into traditional road scheduling models to assign competing repair treatments on a rolling horizontal way. Solutions generated by the MCDA model are feasibly compromised between multiple criteria; however, this model cannot necessarily guarantee an optimal plan due to the nature of the technique. Although linking subjective analysis to an advanced optimization model, thanks to a shared database, has found a promising approach for the spatial decision support involved in operational road decisions. An indication to this effect is that current development resulted in a plan that was economically feasible and technically acceptable to the local road administration. The environmentally considered scenarios were able to increase total costs by about 38% at the expense of a 10% budget reduction compared to the status quo management scenario. The result demonstrates the gaining potential using the combined approach of around 17% only if the available budget increases a little more than 10% of the budget target.

The utility of the approach developed is however not tailored to a specific region. It can be applied anywhere as a generic planning tool to analyze highly complex road repair scenarios. There is still room for improvement in this process to strengthen our ability to do landscape level management both on problem definition and solution strategy.

Pairwise comparisons are important drivers of successful implementation of the MCDA model, and these increased linearly as a number of model elements, raising concerns about responder fatigue. The development of a consolidated decision model, such as a fuzzy-based analytical network process, could hold promise for addressing overwhelming pairwise comparisons with the current approach, while continuing to demonstrate meaningful solutions. Future extension of the current development should aim to integrating the spatial constraints of harvesting and logistics decisions. Such an integration model would embrace a whole class of decision variables synergistically to address these conflicting objectives for tactical planning in forest resource management. Given that decision variables expand, sophisticated solution strategies would also be expected to cope with complexity of the problem and quality of the solution.

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Figure captions

Figure 1.

Figure 2.

Figure 3.

Figure 4.

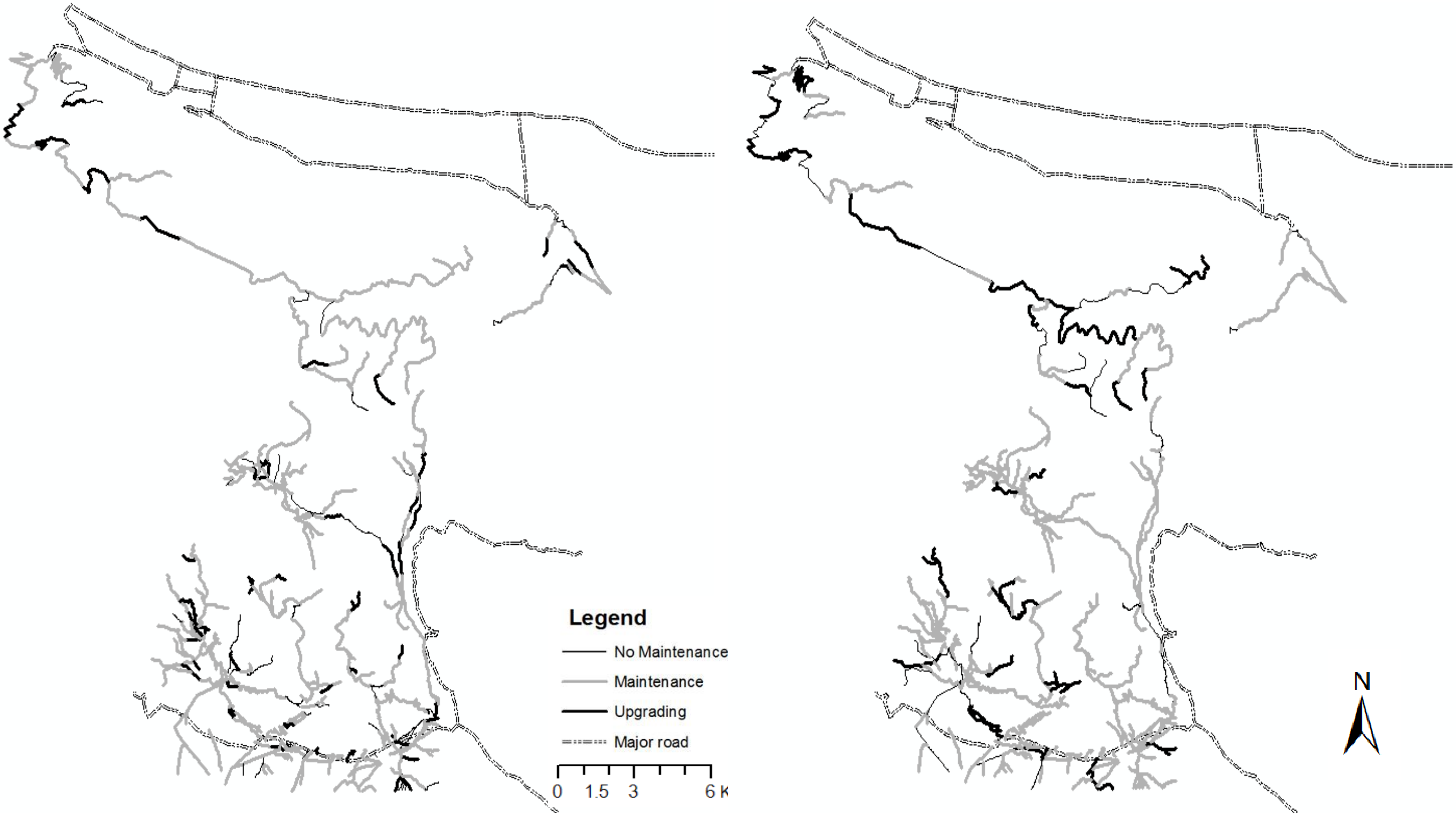
Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9. An illustration of the timing of routine maintenance (period 1 and 2) and periodic upgrading (period 6 and 7) treatments; status quo management (left) and optimization model (right)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Maintenance
Upgrading
Major road
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