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Application of Sensitivity Analysis in Forest Road Networks Planning and Assessment

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ABSTRACT

In the last few years, public awareness has been on the increase about short- and long-term effects of forest roads construction on the environment. Therefore, forest road managers have to be concerned about the negative impacts and mitigate them as much as possible. This research conducted multi-criteria analysis techniques in a useful way to define the effective criteria and propose a model for forest road network planning and assessment so that both economic and environmental costs are minimized. The model was used for evaluating the alternatives and a sensitivity analysis was then performed to verify the model. Results of sensitivity analysis showed that, there were two alternatives out of nine, with the lowest negative impacts. As a result, analytic hierarchy process and sensitivity analysis (AHP-SA) revealed that the criteria slope, soil texture and landslide susceptibility had the highest weight values, respectively, and the criteria soil texture and distance from stream networks and distance from faults were especially sensitive to the changes. In addition, the sensitivity analysis proved that the model proposed in our analysis was almost reliable and stable, and only the first and second priorities were replaced in priority levels when the weight values of criteria were changed. Results showed that the methodology was useful for identifying road networks that met environmental and cost considerations. Based on this work, the authors suggest future work in forest road planning using multi-criteria evaluation and decision making be considered in other regions and that the road planning criteria identified by the experts in this study can be useful.

Keywords: Effective criteria, Environmental assessment, Forest road network, Sensitivity analysis.

INTRODUCTION

Nowadays, changes in forest landscape resulting from road construction increasingly impose environmental impacts to the forest ecosystems. Accessing forests for logging operations and sustainable management of forest resources can only be achieved through an individually tailored forest roads network (Demir, 2007; Abdi *et al*., 2009). In the last few years, public awareness has been on the increase about short- and long-term effects of forest roads on the environment, (Cole and Landres, 1996; Gumus *et al*., 2008; and Acay *et al*., 2008). Hence, forest road managers have to consider not only the economic costs but also the negative impacts of forest roads construction on the natural environment (Lugoa and Gucinski, 2000; Dutton *et al*., 2005).

Road construction and maintenance operations are the most costly and destructive activities in forestry, for example; the frequency of the roadside landslide has been proven to be roughly five times higher than the other areas (Larsen and

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Parks, 1997). Furthermore, forest roads are globally recognized as a main source of sediment yield and pollution of off-site water (Arnaez *et al*., 2004; Forsyth *et al*., 2006; Fu *et al*., 2010) and also ecological fragmentation and disturbance in forest landscapes (Forman *et al*., 1997; Delgado *et al*., 2007). Forest roads alter the landscape spatial pattern with artificial linear gaps, generate abrupt edges and finally cause habitat and biodiversity losses (Forman and Alexander, 1998; Hui *et al*., 2003; Delgado *et al*., 2007). To reduce these negative impacts, forest road managers need to look for ways on how to develop road networks and improve environmental soundness and public acceptance of road construction activities (Heinimann, 1996; Gumus *et al*., 2008). Consequently a functional approach is needed to take into account all the technological, economic and environmental factors in road networks planning, so that both economic and environmental costs are minimized.

Multi-criteria analysis techniques are well known decision-support tools for dealing with such complicated decision making, where technological, economic and environmental aspects have to be covered to obtain an overall assessment of the decision alternatives (Pukkala, 2002; Marinoni, 2004; Malczewski, 2006; Vadrevu *et al*., 2010; Biswas *et al*., 2011). For evaluating the numerous criteria, Analytic Hierarchy Process (AHP) has become one of the most widely used multi-criteria decision support systems to help users by breaking down these complicated decisions into a hierarchy (Shiba, 1995; Akash *et al*., 1999; Chan *et al*., 2000; Gercek *et al*., 2004; Coulter *et al*., 2006; Sener *et al*., 2011). This methodology is a powerful and flexible decision making process to help decision makers set priorities and make the best decision when both qualitative (intangible) and quantitative (tangible) aspects of a decision need to be considered (Gercek *et al*., 2004). Furthermore, AHP provides a methodological framework within which the inconsistency in judging the relative importance of criteria in a site suitability analysis can be both detected and corrected (Tudes and Yigiter, 2010). However,, before using an analytic hierarchy process, all the criteria required in forest road planning and assessment have to be defined and standardized based on an efficient approach. The Delphi technique is a conventionally adopted qualitative forecasting method (Austen and Hanson, 2008) and has been proven to be an effective means of identifying the required and effective criteria in the assessment procedures (Keeny and Raiffa, 1976; Taylor, 1984; Steinmüller, 2003). It also will lead to a consensus and agreement on selecting criteria within a panel of experts (Loo, 2002; Taylor and Ryder, 2003; Curtis, 2004).

In this study, like most multi-criteria based evaluations, the weights of criteria are the principal input parameters that may vary in different circumstances. Indeed, in the AHP framework, their values depend not only on the weighting method chosen but also on the judgments expressed by the involved experts (Pasqualini *et al*., 2011; Sadeghi-Niaraki *et al*., 2011). Also inputs (criteria) are subject to various sources of uncertainty including incomplete information and understanding about effective criteria and their importance, and the mechanisms by which the criteria affect the problem. This uncertainty compels a limit on the confidence in the output of the model (Hasmadi and Taylor, 2008; Samani and Solimani, 2008; Sadeghi-Niaraki *et al*., 2011). Thus, it is legitimate to perform a Sensitivity Analysis (SA) to investigate the sensitivity of the ranking of the alternatives when the priorities of the criteria are changed. The SA process can help examine the reliability and the sensitivity of a model and diminish uncertainty in outputs (Mészáros and Rapcsák, 1996; Crosetto *et al*., 2000 Sadeghi Ravesh *et al*., 2011).

In this article, we show how these methods can be truly combined and applied in a useful way for such analysis, to define the effective criteria by Delphi process and rank them via pair-wise comparison matrices and finally evaluate the final road network

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alternatives by using AHP-SA methodology for selecting the most preferred alternatives.

MATERIALS AND METHODS

Study Area

This study was carried out in *Baharbon* district of *Kheyrud* forest, an uneven aged hardwood forest in Northern *Iran* (Ahmadi *et al*., 2011; Esmailzadeh *et al*., 2011), approximately on the coordinates 36°29' N and 51°40' E (Figure 1). The study area is situated in a mountainous region which covers 1,400 hectares with slopes varying between 0 and 105%. The relief has a very irregular topography, and the elevation ranges from 900 to 2,200 masl. Most parts of the study area were covered with a set of different limestone types (especially argillaceous limestone) with coal bearing shale. The study site mainly includes a fine soil texture and is rather susceptible to landslide occurrence and also to surface erosion.

A three-round Delphi was conducted to specify the most effective criteria in forest road development with regard to the professional experiences and judgments of 9 forest engineering experts. Individual interviews were conducted with each participant in Round 1, Rounds 2 and 3 of Delphi consisted of mail-out surveys to give their feedback regarding to the responses obtained in Rounds 1, 2 and 3, respectively. They were invited and given questionnaires to define the criteria which are more important in terms of affecting forest road networks assessment.

Afterwards, a pair-wise comparison questionnaire of the criteria selected in the previous stage was developed and sent to the panel members who participated in Delphi process, to rank the criteria regarding their effect and importance in the assessment procedures. The criteria have different effects and thus different importance weights in evaluating the road network alternatives. The responses were then analyzed and combined in the Expert Choice (EC) software (if the consistency ratio was acceptable), and finally the importance weights of all criteria were obtained.

ArcGIS and IDRISI software packages were then used to prepare (with 20 m pixel size) and standardize the map layers of the suggested criteria. Standardization of each data layer into a comparable suitability of values was performed using the fuzzy set membership functions (Eastman, 2003). This module is designed to assign each pixel in a map to a fuzzy set membership function. The main advantage to this approach for our work is that it avoids setting hard or arbitrarily established thresholds between different levels of suitability. Output map layers of the criteria were scaled from 0 (zero suitability of class membership) to 255 (100% suitability of class membership) for each layer in our analysis. In this way each map layer of the criteria will

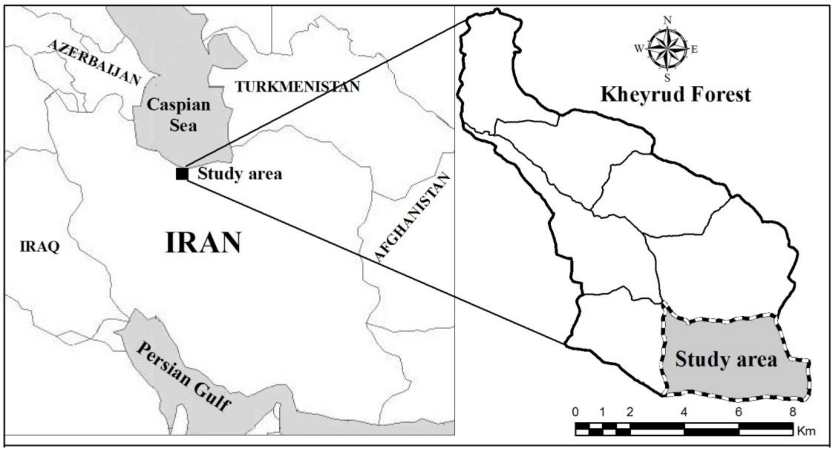

Figure 1. Location of the study area in Kheyrud forest.

have a value ranging from 0 to 255, to make it possible to conduct the first stage of the evaluation.

Then, nine road network alternatives were designed using PEGGER, an ArcView GIS extension (Rogers, 2005), with respect to the forest road technical standards. The designed road routes were converted from vector to a raster format with 20 m pixel size and value of 1. Then each one of the new road networks maps was overlaid with each fuzzy map layer one by one, to find the average standardized fuzzy value of each criterion at the road network alternatives area. The EC software was used once more, to compare and analyze the 9 alternatives. The alternatives were compared against each other with regard to the values extracted from each fuzzy map layer (the early score of the alternatives) and then the preferred weights of the alternatives were obtained with regard to each criterion.

To determine the final score (preferred weights of the alternative with regard to all criteria) of the alternatives, Equation (1), the hierarchical composition principle, was used (Saaty, 1980).

$$\mathrm{Re}\,sult = \sum_{j=1}^{n}\sum_{i=1}^{m} w_j W_i \qquad (1)$$

Where, w_j is the importance weight of the j^{th} criterion and W_i is the preferred weight of the i^{th} alternative with regard to the j^{th} criterion, and finally *result* is the final score of the alternatives (or preferred weights of the alternative with regard to all criteria).

Afterwards, a sensitivity analysis of results was conducted to check what may happen to priority levels of road networks when the values of criteria are changed. SA, which generates conditions of possible rankings of decision alternatives under different circumstances, has been performed in our study by varying the weight values of plus or minus 2, 5 and 10%. In performing sensitivity analysis for a forest road network planning we deal with such criteria as slope, soil texture, landslide susceptibility, etc. Given the existing circumstance of the study area and also considering the nature of the effective criteria in this study which are all land based, they would not be changeable so much. In fact, the importance weight of slope or soil texture etc., cannot abruptly fluctuate. Thus, it is not legitimate to consider changes more than 10%. Figure 2 illustrates the decision making process in this study.

RESULTS

The participants in Delphi process suggested a set of criteria that affect forest road planning, but some of the suggested criteria had similar conditions throughout the study area and were

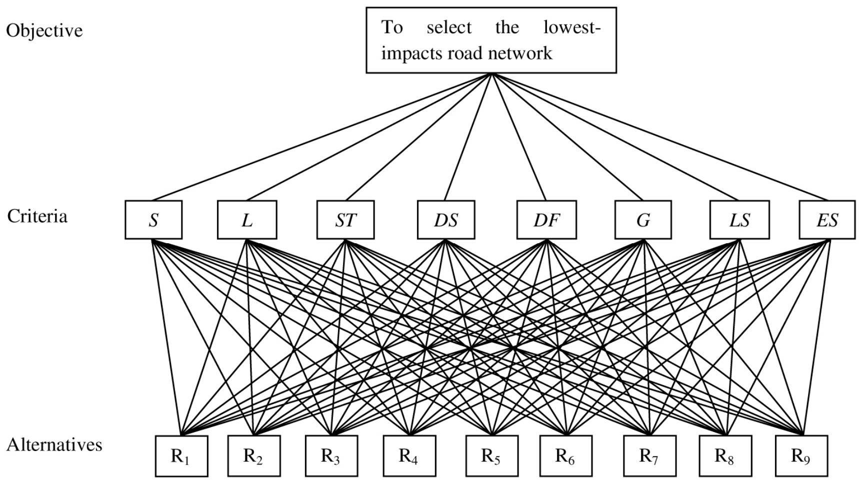

Figure 2. Description of decision making process. R: Road network alternatives (R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8 and R_9), Criteria (S: Slope; L: Lithology; ST: Soil texture; DS: Distance from stream; DF: Distance from faults; G: Geology; LS: Landslide susceptibility; ES: Erosion susceptibility).

therefore removed. Also our study site was limited by the lack of two criteria and they were thus ignored. Finally, panel members declared their consensus and agreement on 8 criteria including slope, lithology, soil texture, distance from stream network, distance from faults, geology, landslide susceptibility and erosion susceptibility. Thus, Delphi was consummated by identifying the aforementioned criteria as effective and important parameters in forest road network planning.

The results of performing pair-wise comparisons for the effective criteria were analyzed in the EC software. All consistent judgments were combined and then importance weights of the criteria were obtained. The consistency ratio was 0.02 and up to standard (Saaty 2000). The following model, obtained by EC, shows the importance weights of effective criteria in road networks analysis:

$$Model = 0.320S + 0.051L + 0.191ST + 0.045DS + 0.068DF + 0.047G + 0.187LS + 0.091ES \quad (2)$$

Where, *S*: Slope; *L*: Lithology; *ST*: Soil texture; *DS*: Distance from stream networks; *DF*: Distance from faults; G: Geology; *LS*: Landslide susceptibility, *ES*: Erosion susceptibility.

Nine road network alternatives were designed (Figure 3) and overlaid with a 20 m wide corridor with the standardized map layers so that the average standardized fuzzy value of each criterion at the alternative area was extracted (Table 1). Therefore in this way, an early score was obtained for each road network alternative.

Table 2. The final score of the road network alternatives.

Alternatives	Length (km)	Final score	AHP ranking
No. 1	10.197	0.033	9
No. 2	11.389	0.101	6
No. 3	13.979	0.097	7
No. 4	13.565	0.058	8
No. 5	17.434	0.174	1
No. 6	16.859	0.119	4
No. 7	16.638	0.144	3
No. 8	19.484	0.105	5
No. 9	19.073	0.168	2

To assess the alternatives, the decision making group developed another pair-wise comparison matrix and weighted the alternatives against each other with regard to the values in Table 1. Results of the assessment and AHP ranking are given in Table 2.

Since the weights of criteria, obtained by the experts' judgments, may vary in different circumstances, we cannot absolutely introduce the best alternative yet (Table 2). Therefore an SA was performed to investigate how changeable the priority level of the most preferred alternative is when the weights of criteria are changed. Results of SA are shown in Table 3.

Changes in the weights values of the criteria which caused changes in the priority levels of the three most preferred alternatives are illustrated in Figures 4.

Table 1. The values (early score) of road network alternatives on each criterion fuzzy map layer.

Alternatives		S^a	L^b	ST^c	DS^d	DF^e	G^f	LS^g	ES^h
No. 1	The values of the alternatives on map layers (Per km)	7360.45	5498.55	1785.90	6594.40	10955.10	5498.55	6297.95	12687.95
No. 2		7726.20	5498.65	2306.65	7071.80	11110.65	5498.65	6335.20	12693.35
No. 3		7751.90	5498.90	2252.75	7095.40	11398.90	5498.90	6452.10	12703.30
No. 4		7745.50	5498.90	1802.25	7280.35	11318.15	5498.90	6346.20	12702.95
No. 5		8038.55	5499.10	2200.90	7605.75	11603.70	5499.10	6597.70	12712.35
No. 6		7948.35	5499.10	2183.05	7570.65	11575.95	5499.10	6501.15	12711.40
No. 7		7970.15	5499.05	2215.65	7640.25	11597.35	5499.05	6604.45	12710.15
No. 8		7890.40	5499.20	2161.10	7816.10	11715.00	5499.20	6437.90	12716.05
No. 9		7943.80	5499.20	2168.90	8017.15	11728.50	5499.20	6641.40	12715.55

[a] Slope; [b] Lithology; [c] Soil texture; [d] Distance from stream networks; [e] Distance from faults, [f] Geology; [g] Landslide susceptibility, [h] Erosion susceptibility.

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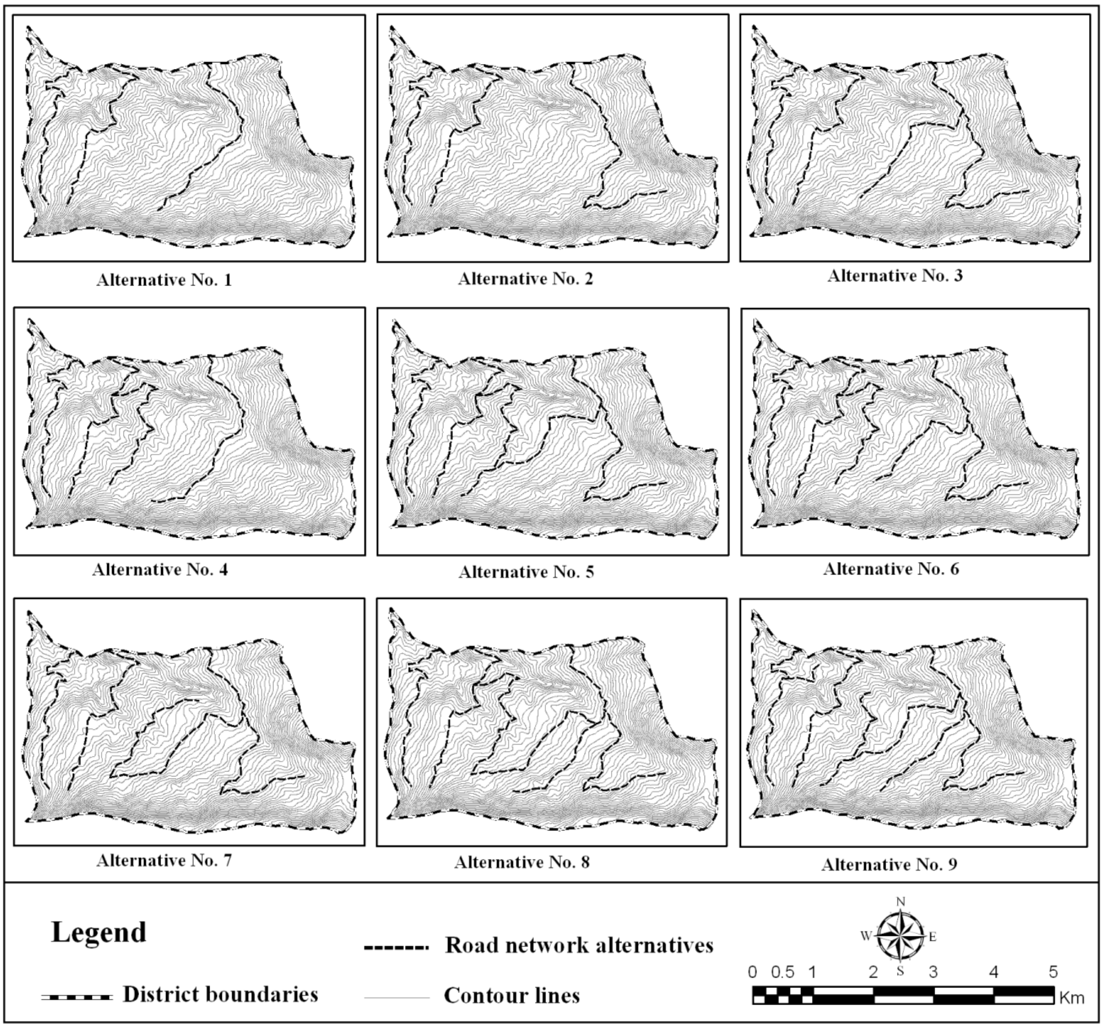

Figure 3. Road network alternatives.

Table 3. The status of the priority levels of the alternatives after performing SA (Sensitivity Analysis).

Criteria	Varying the weight values of criteria					
	+2%	-2%	+5%	-5%	+10%	-10%
S[a]	unchanged	unchanged	unchanged	unchanged	unchanged	Changed[k]
L[b]	unchanged	unchanged	unchanged	unchanged	unchanged	-
ST[c]	changed	unchanged	changed	changed	changed	changed
DS[d]	unchanged	unchanged	changed	changed	changed	-
DF[e]	unchanged	changed	changed	changed	changed	-
G[f]	unchanged	unchanged	unchanged	unchanged	unchanged	-
LS[g]	unchanged	unchanged	unchanged	unchanged	changed	unchanged
ES[h]	unchanged	unchanged	changed	unchanged	changed	-

[a] Slope; [b] Lithology; [c] Soil texture; [d] Distance from stream networks; [e] Distance from faults, [f] Geology; [g] Landslide susceptibility, [h] Erosion susceptibility. [k] Underlined cells refer to the replacement among the first, second and third priority levels of the road networks.

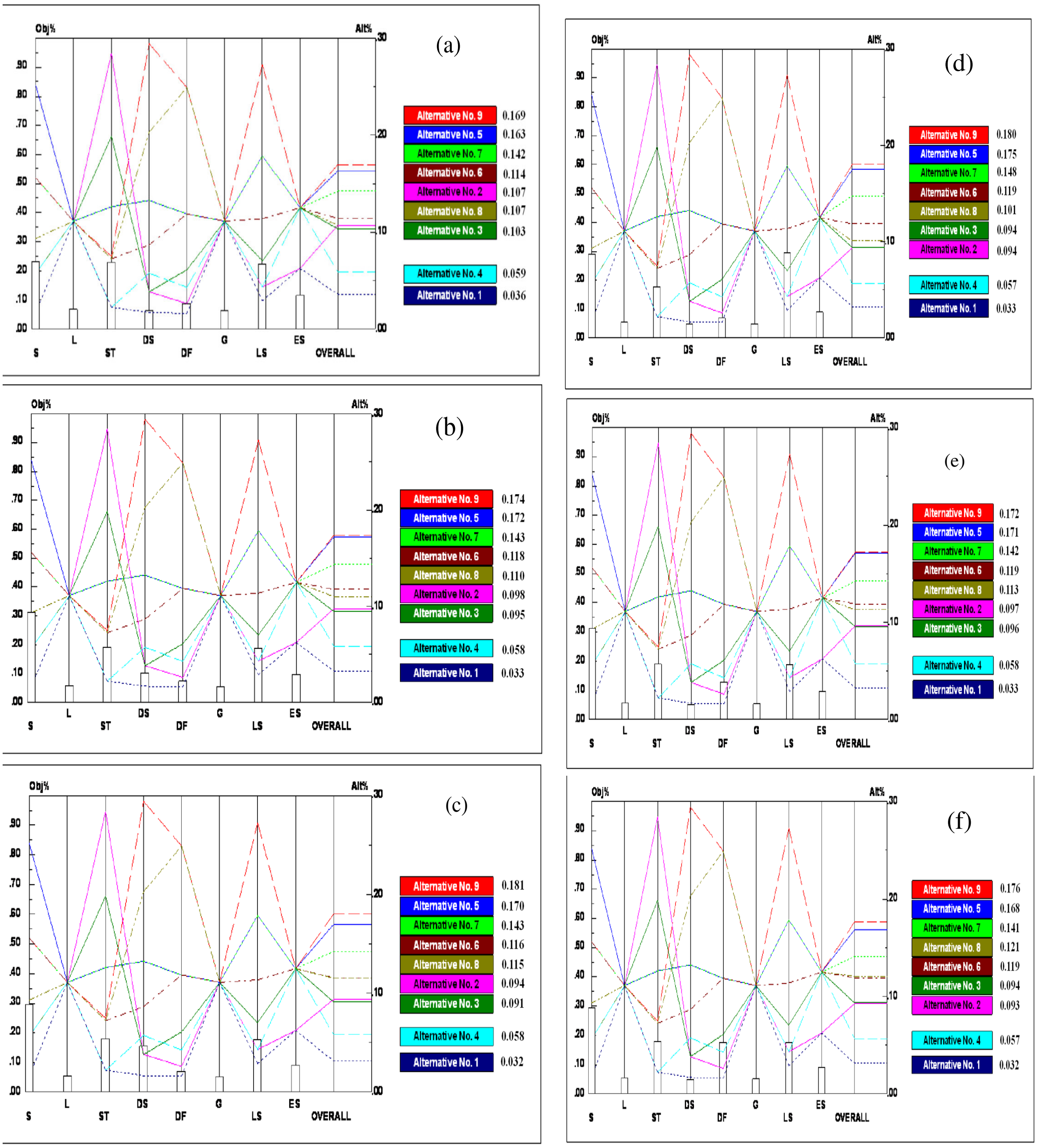

Figure 4. The result of SA (Sensitivity Analysis) for the criteria which caused changes in the three most preferred alternatives. a) Varying the weight value of minus 10% in the criterion Slope, b) Varying the weight value of plus 5% in the criterion Distance from Stream Networks, c) Varying the weight value of plus 10% in the criterion Distance from Stream Networks, d) Varying the weight value of plus 10% in the criterion Landslide, e) Varying the weight value of plus 5% in the criterion Distance from Faults, f)

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DISCUSSION

Road network planning deals with several objectives and factors in sustainable forest management. Therefore a functional approach is needed to lead to an efficient road network to consider most of the objectives. The road networks with shortest path and economically lowest-cost (Dean, 1997; Chung and Sessions, 2001; Aruga, 2005; Akay, 2006) are technically optimized, but may have not been the best path environmentally. Therefore, in this study the GIS-based multi-criteria analysis techniques were applied for defining and involving most of the required factors in the assessment procedure (Malczewski, 2006; Acay *et al*., 2011) to optimize a road network technically, economically and environmentally as well.

Analyzing the experts' judgments showed that slope, soil texture and landslide susceptibility were the three most important criteria, respectively [Equation (2)]. Abdi (2009) derived the highest weight values for the slope and soil texture in road network planning. According to the result of analytic hierarchy process in the assessment of the nine road networks, the road alternatives No. 5, 9 and 7 were found to be the three most preferred alternatives, with final scores of 0.174, 0.168, and 0.144, respectively (Table 2). Thus, in this case the alternative No. 5 can be introduced as the lowest-impact road network in our study site. However, as in the AHP method the weight values of criteria are determined by a group of different experts' judgments, the values may vary in a narrow range and cause some changes in the ranking of alternatives (Hasmadi and taylor, 2008; Pasqualini *et al*., 2011). Therefore, any one of the three aforementioned alternatives, which had almost the same final score, may be considered as the best road network in the study area. As proven by SA (Figures 4-1 and -2), the first and second priority levels were changeable when the weight values of the criteria, slope, landslide susceptibility, distance from stream networks and distance from faults were changed. Varying the weight value of minus 10% of *S* led to the new values of 0.163 and 0.169 for alternatives No.5 and 9, respectively. The new values for alternatives No. 5 and 9 were 0.175 and 0.180, respectively, when the weight value of *LS* was increased 10%. Also results of SA showed that alternatives No. 5 and 9 reached the new values of 0.172 and 0.174 (by varying the weight value of plus 5% of DS), 0.170 and 0.181 (by varying the weight value of plus 10% of DS), 0.171 and 0.172 (by varying the weight value of plus 5% of DF), and 0.168 and 0.176 (by varying the weight value of plus 10% of DF), respectively. Hence, alternative No. 9 moved from the second priority to the first under the new circumstances. The other changes in the weight values of the criteria did not lead to changes in the first, second and third priority levels, thus alternative No. 5 still was the best alternative. As shown in the Table 3, varying the weight values of the criteria soil texture and erosion susceptibility causes some changes in the ranking of alternatives, but these changes are only related to the sixth, seventh and eighth priority levels, and the other priority levels were constant.

By SA, in addition to investigating the stability of the model, we can also identify criteria that are especially sensitive to weight changes (Sadeghi-Niaraki *et al*., 2011). The SA performed in this research proved that the criteria *ST*, *DS*, and *DF* were especially sensitive to the changes (Table 3). Although the criterion *ST* did not lead to changes in the three most preferred road networks, it is remarkable that only varying the value of plus 2% for this criterion, caused changes in the other priority levels. The criteria *S* and *LS* were not very sensitive to the changes but they resulted in changes in the first and second priorities of the road networks. As changes in the weight values of the criteria did not lead to major changes in the results (for example there was no replacement between the first priority and the very low priorities) and only the first and second priorities were replaced, it is concluded that the model outcomes are almost stable in providing an efficient assessment in forest road networks planning.

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The AHP-SA methodology showed well that either one of the road networks No. 5 and 9 can be developed in the study area, and the final decision for the selection will depend on the objective of the forestry management unit.

The results also demonstrated that combining GIS and PEGGER with multi-criteria techniques applied in this work, enables us to design and assess forest road networks as many as possible and finally to properly select the lowest-impact alternative. Also by using this methodology and providing Table 1, decision makers can conduct a primary assessment in forest road network planning. For example, by investigating the characteristics of the selected alternative in Table 1, its weakness and strength can be determined. Therefore, forest road managers can select and design a road network with these characteristics and save time and money in the construction phase.

The combination of the methodologies conducted in this study and the road planning criteria identified by the experts are suggested for future work in forest road planning in other regions.

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آنالیز حساسیت در برنامه ریزی و ارزیابی شبکه جاده جنگلی

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چکیده

امروزه با افزایش نگرانی‌های عمومی در رابطه با اثرات محیط زیستی کوتاه مدت و بلند مدت ناشی از توسعه جاده در جنگل، مسائل محیط زیستی و به حداقل رساندن این اثرات در هنگام طراحی و ارزیابی شبکه جاده جنگلی از اهمیت ویژه‌ای برخوردار می‌باشد. لذا در این مطالعه با استفاده از تکنیک‌های

مختلف ارزیابی چند معیاری ابتدا معیارهای تاثیرگذار در طراحی و ارزیابی شبکه جاده تعیین و سپس چارچوبی کارآمد به منظور برنامه ریزی و ارزیابی شبکه جاده ارائه شد تا علاوه بر رعایت مسائل فنی و اقتصادی، اثرات محیط زیستی ناشی از آن نیز حداقل گردد. مدل ارائه شده ابتدا جهت ارزیابی گزینه‌ها، به کار گرفته شد و سپس آنالیز حساسیت نتایج حاصل از مدل انجام گردید. طبق نتایج حاصل از اجرای آنالیز حساسیت، دو گزینه شبکه جاده از نه گزینه طراحی شده به عنوان گزینه بهینه با حداقل اثرات پیشنهاد شدند. نتایج AHP-SA نشان دادند که معیارهای شیب زمین، بافت خاک و حساسیت به زمین لغزش به ترتیب بیشترین اهمیت را به منظور طراحی جاده با حداقل اثرات دارند و بیشترین حساسیت گزینه‌های شبکه جاده در این مطالعه نسبت به معیارهای بافت خاک، فاصله از آبراهه و فاصله از گسل بوده است. همچنین نتایج حاصل از آنالیز حساسیت نشان دادن که با ایجاد شرایط متغیر و حالت‌های مختلف فرضی در به کار گرفتن داده‌ها تغییر زیادی در خروجی مدل موجب نشده و تنها اولویت دوم گزینه‌ها با اولویت اول جابجا شده است. طبق نتایج، چارچوب ترکیبی به کار گرفته شده در این مطالعه، به خوبی می‌تواند در تعیین شبکه جاده‌ای با حداقل هزینه و اثرات محیط زیستی استفاده شود. با توجه به نتایج این تحقیق، استفاده از روش‌های مختلف ارزیابی و تصمیم گیری چند معیاری و همچنین معیارهای تاثیر گذار در طراحی شبکه جاده که در این مطالعه تعیین شده، در برنامه ریزی شبکه جاده جنگلی برای سایر مناطق قابل توصیه است.