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Building Consensus in Environmental Impact Assessment Through Multicriteria Modeling and Sensitivity Analysis

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ABSTRACT / Multicriteria decision analysis (MCDA) increasingly is being applied in environmental impact assessment (EIA). In this article, two MCDA techniques, stochastic analytic hierarchy process and compromise programming, are combined to ascertain the environmental impacts of and to rank two alternative sites for Mexico City's new airport. Extensive sensitivity analyses were performed to determine the probability of changes in rank ordering given uncertainty in the hierarchy structure, decision criteria weights, and decision criteria performances. Results demonstrate that sensitivity analysis is fundamental for attaining consensus among members of interdisciplinary teams and for settling debates in controversial projects. It was concluded that sensitivity analysis is critical for achieving a transparent and technically defensible MCDA implementation in controversial EIA.

Environmental impact assessment (EIA) is increasingly at the center of public debate regarding the implementation of large-scale infrastructure projects. EIA is a systematic study aimed at appraising the likely effects of development projects on the environment. Under this context, EIA entails the consideration of the relevant environmental issues so that authorities can make well-informed decisions concerning project approval and, if appropriate, set the conditions for the mitigation of the foreseeable impacts (Hollick 1980; Ortolano 1997). In addition, EIA also plays a crucial role in the decision-making process of projects that involve conflicting issues with high political content, such as site selection in large-scale infrastructure planning. In controversial cases, different stakeholders bring into play their own perspectives and information to either support or oppose a project. In such cases, an EIA must supply the technical and scientific arguments needed for settling disputes among the stakeholders and prevent ideologically based opinions from influencing the decision-making process (Lawrence 2000; Leknes 2001).

KEY WORDS: Airport; Analytic hierarchy process; Compromise programming; Conflict resolution; Environmental impact assessment; Mexico; Participatory Planning; Sensitivity analysis; Suitability Analysis; Uncertainty

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Contentious infrastructure projects raise some consequential issues in EIA. An EIA requires precise definitions of standards, goals, and visions related to the notion of ''environmental quality,'' yet, environmental quality is an abstraction generated by value-laden and subjective reasoning (Hull and others 2003), so such definitions are always relative to specific interests and preconceptions. Furthermore, although the subjectivity of the stakeholders can be easily recognized, it is not often acknowledged that the judgments of the experts themselves can reflect similar biases (Beattie 1995; Kontic 2000). In contrast, a stakeholder may contest an EIA if the outcome of the assessment does not support a particular stance, claiming that the analyses are incomplete, flawed, and biased (Beattie 1995; Crowfoot and Wondolleck 1990; Wondolleck, 1985). Therefore, an EIA should consist of a thorough appraisal of impacts relative to antagonistic conceptions of environmental quality, including those generated even by vested interests, deep-seated emotions, and subjective reasoning (Rauschmayer 2001).

Although the existence of opposing viewpoints about a project underscores the need for an unbiased EIA, identifying which environmental factors should be included in the analysis demands considerable effort

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and skill. One major practical challenge is how the opposing viewpoints and values can be systematically examined under the interdisciplinary context of an EIA. This is a matter of utmost importance because the ability of a group of experts to predict impacts is determined by their understanding of the system under study. Because such understanding is generally based on subjective judgments and scarce data about complex and uncertain processes (Holling 1978; Hollick 1981; Lawrence 1993), it is not uncommon for experts to express a lack of confidence in their judgments or even for experts in the same field to legitimately disagree in their judgments about the significance of impacts. Because data for predicting impacts are usually unavailable and the urgent need for results precludes carrying out applied research to obtain better information (Bojórquez-Tapia 1989), these disagreements and analytic disputes cannot be scientifically settled. This ambiguity only serves to fuel the challenges of those stakeholders who wish to contest the EIA's conclusions. In consequence, a fundamental issue is how to build consensus among experts and stakeholders about the foreseeable environmental impacts of a controversial project.

Multicriteria decision analysis (MCDA) has been successfully used for dealing with the manifold detail inherent in consensus building in the EIA process (Bakus and others 1982; Lahdelma and others 2000; Janssen 2001; Ramanathan 2001; Wenstøp and Seip 2001). MCDA allows an interdisciplinary group of experts to decipher their understanding about the environmental impacts of a project and formally identify decision criteria (i.e. the environmental attributes) and rank alternatives in terms of explicit decision rules (Bana e Costa 2001; Janssen 2001; Munda 2003).

In this article, we show an MDCA implementation that allowed a group of experts with contrasting and politicized opinions not only to agree on the foreseeable impacts generated by the construction and operation of a highly controversial project—the Mexico City International Airport (henceforth, the airport)—but to also gain confidence in the rigor of the EIA process. Our MCDA implementation combined the analytic hierarchy process (Saaty 1980) to derive the importance weights for the environmental attributes and compromise programming (Szidarovszky and others 1986) to rank the two alternative sites to the airport with respect to the foreseeable environmental impacts. We tested the stability of the results by obtaining the rank reversal probabilities produced by uncertainty in the cardinal comparisons required by the Analytic Hierarchy Process (AHP) (Saaty and Vargas 1987) and in the performance of the alternatives on each environmental attribute (Anderson and others 2001; Triantaphyllou 2000).

It should be noted that the emphasis of our analysis was on the probability of changes in rank ordering given uncertainty in the weights arising from the preference ratios in the AHP. Accordingly, we employed a stochastic formulation of the AHP to examine the uncertainty in the importance weights of the environmental attributes (see Hahn 2003; Saaty and Vargas 1987; Stam and Duarte Silva 1997; Van den Honert 1998). Therefore, this study is unrelated to the well-documented rank irregularities caused by the addition or deletion of alternatives in the AHP using deterministic, single-valued paired judgments (see Belton and Gear 1983; Haines 1998; Leary and Wan 1998).

In the end, the MCDA implementation made possible the consolidation of the interdisciplinary information into a unified decision making framework. It in fact provided a means for a systematic examination of all the relevant environmental factors. Thus, the MCDA implementation allowed the group of experts to acquire a better understanding of the implications of the uncertainties in their judgments and data and thus facilitated consensus about foreseeable impacts of the project. Hence, the group concluded that the rankings of the alternative two sites were statistically indistinguishable. In this way, the MCDA produced a transparent and technically defensible EIA.

Decision Context

The project for the airport has a history of five decades. Keeney and Raiffa (1976) presented an assessment of three alternative sites for the airport as a case study in their seminal book, whereas Lavelle and others (1997) applied uncertainty analysis to the same problem. Although the two alternatives in our case study are different, the justifications for the project have remained unchanged, namely to satisfy the growth in demand for cargo and passengers air travel while minimizing costs and access times to users. With time, the alternative sites changed, and the final sites considered by the ASA (Aeropuertos y Servicios Auxiliares, Airports and Supporting Services) of the SCT (Secretaría de Comunicaciones y Transportes, Ministry of Communication and Transportation) included (1) option Hidalgo located 80 km North of Mexico City in the state of Hidalgo and (2) option Texcoco located 15 km East of Mexico City in the state of Mexico.

The project was perceived as long overdue by the ASA, and that sense of urgency added political pressure to the site-selection process. The two alternative sites considered for the airport generated a competition between the governments of the states of Mexico and Hidalgo. Each of these governments assembled teams of experts who lobbied on behalf of their own site and emphasized the negative aspects of the alternative.

The general opinion among high-ranking officials in the federal government was that the final decision required the approval of the SEMARNAT (Secretaria de Medio Ambiente y Recursos Naturales, Ministry of the Environment and Natural Resources). However, the official requirements for the project approval created a planning conundrum. The environmental authorities were not able to rule in conformity to law because a final design for the airport facilities and associated infrastructure was not available, but the ASA could only prepare a final design once the appropriate site was identified.

SEMARNAT decided to put an end to that planning conundrum through an independent appraisal of the environmental issues raised by the states of Hidalgo and Mexico. The INE Instituto Nacional de Ecología (National Institute of Ecology) was the federal agency in charge of supervising an environmental comparison of the two alternative sites. The INE hired PUMA (Programa Universitario de Medio Ambiente of the National Autonomous University of Mexico, University Environmental Program) to carry out a comprehensive EIA of the two sites using all the information available including that supplied by the states of Hidalgo and Mexico. PUMA integrated an interdisciplinary team and conducted the comparative evaluation during 2-month period, from June to the end of July 2001. The evaluation focused on the issues identified as relevant by the environmental authorities: hydrology, air pollution, urban development, land-use potential, geology, biodiversity, and aviation hazards. Unlike the other criteria, the latter was deemed necessary to ponder the effects of environmental attributes on airport operations.

Implementation of the MCDA

Structuring the Problem

The appraisal of impacts of the airport presented the typical challenges of interdisciplinary group decision-making problems (see Bettinger and Boston 2001). In general, the understanding of the experts on the behavior of the whole biophysical system was sketchy and fractional. Hence, the experts had a loose and biased notion of the possible impacts at the beginning of the assessment process. Furthermore the team of experts was inexperienced with MCDA approaches. Consequently, an iterative scheme was devised to deal with difficulties related to the limitations of information, understanding, and experience.

The iterative scheme aimed at stimulating interdisciplinary discussions and feedback among the experts. Accordingly, the interdisciplinary team was divided into an integration group (responsible for the implementation of the MCDA techniques) and six specialist groups (i.e., hydrology, air pollution, urban development, land-use potential, geology, and biodiversity). Three workshops were carried out to address the complexity of the EIA and to allow the experts become acquainted progressively with the MCDA techniques. During the period between workshops, each specialist group independently assessed the environmental impacts at each alternative site under the supervision of the integration group.

In the first workshop, the experts were divided in working groups according to their area of specialization. The AHP was carried out in each working group, using the software Expert Choice (DSEE 1995), so that the experts could familiarize themselves with the technique. The result were presented and discussed by the group in a plenary session. At the end of the workshop, it was agreed that the decision criteria in the second hierarchy level should encompass the seven relevant issues identified by the environmental authorities.

After the first workshop, each specialist group worked individually in refining the initial hierarchy structure and the pairwise comparisons among the subcriteria of their specialty. This allowed them to ascertain the adequacy of the selected environmental attributes for the EIA and to eliminate the redundant subcriteria. Once a final set of decision criteria was delineated, the specialist groups focused on appraising the magnitudes of the potential environmental impacts. The subcriteria under aviation hazards were evaluated jointly by experts of the related disciplines.

In the second workshop, the experts were divided into eight interdisciplinary working groups and executed the AHP in a second iteration. This allowed the experts to justify their reasons for or against the expected impacts and the related subjective judgments. The results of the working groups were discussed in a plenary session in which the group of experts generated a unified hierarchy structure (hereafter hierarchy structure A; Fig. 1a), three different scenarios for the EIA (see later), and the interval judgment matrix (Table 1).

The three scenarios reflected the two contrasting views by the experts about the likely effects of the airport on urban sprawl. For scenario 1, the assumption was that the construction and operation of the airport

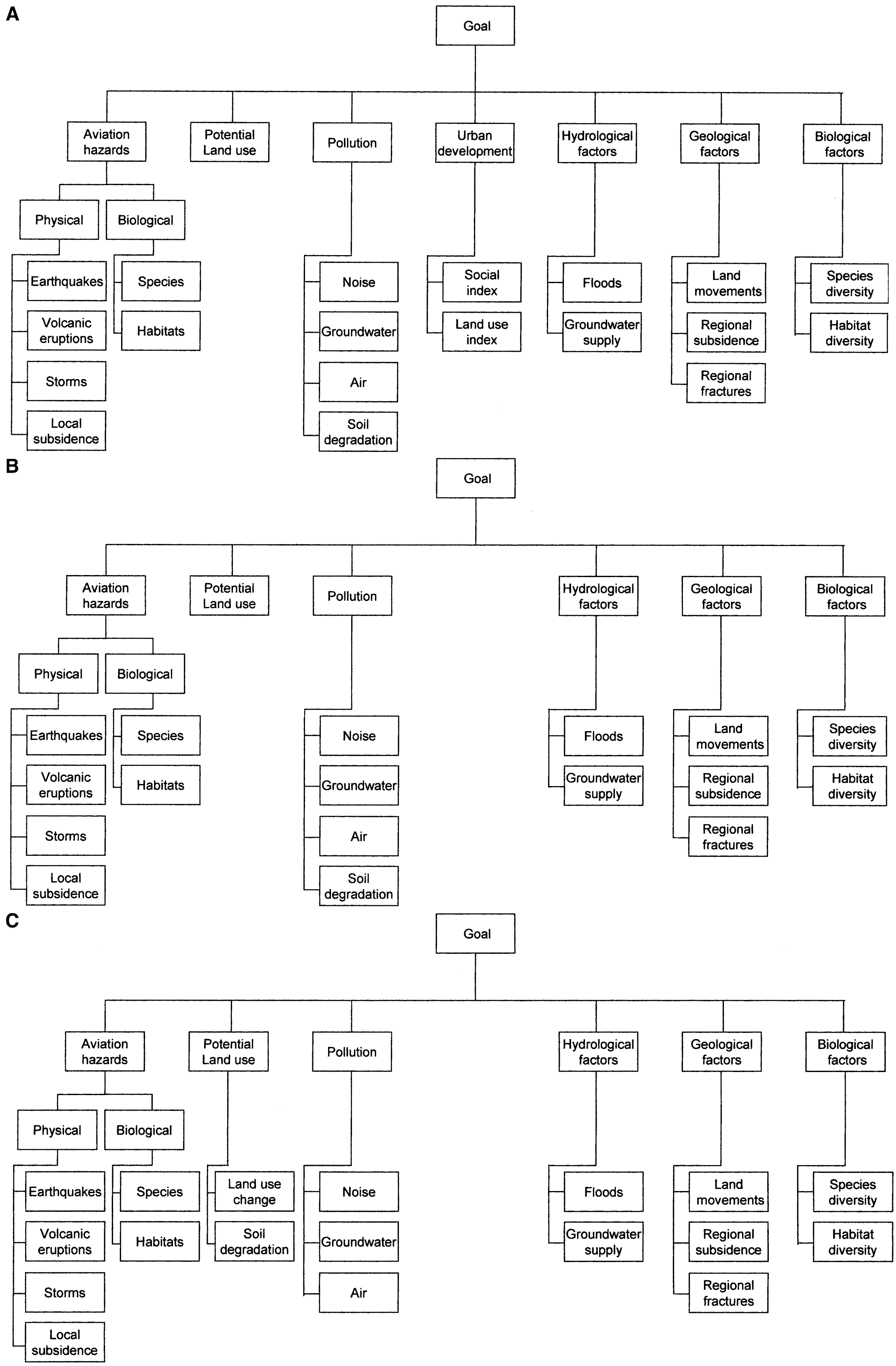

Figure 1. Hierarchy structures developed for the airport environmental assessment. **(A)** Hierarchy structure A. **(B)** Hierarchy structure B. **(C)** Hierarchy structure C.

Table 1. Interval judgment matrix for the decision criteria at the second hierarchy level of the airport environmental assessment

Decision criterion	C_2	C_3	C_4	C_5	C_6	C_7
Aviation hazards (C_1)	[1/7, 5]	1/5	[1/7, 1]	[1/7, 1/4]	1/6	[1/5, 1/4]
Biological factors (C_2)	1	[1/5, 1/2]	[1/5, 1/2]	[1/7, 1]	[1, 4]	[1/3, 2]
Pollution (C_3)		1	[1/5, 7]	[1/6, 1]	[1/3, 7]	3
Urban development (C_4)			1	[1/6, 4]	[1/4, 4]	[1/4, 4]
Hydrologic factors (C_5)				1	5	[1, 5]
Geologic factors (C_6)					1	1/3

Table 2. Decision matrix for the airport environmental assessment[a]

Hierarchy level				Standardized value by scenario					
First	Second	Third	Fourth	H1	T1	H2	T2	H3	T3
			Earthquakes	0.988	0.012	0.988	0.012	0.988	0.012
			Volcanic eruptions	0.988	0.012	0.988	0.012	0.988	0.012
	Aviation hazards	Physical	Storms	0.845	0.155	0.845	0.15	0.845	0.155
			Local subsidence	0.988	0.012	0.988	0.012	0.988	0.012
		Biologic	Species	0.542	0.458	0.486	0.514	0.601	0.399
			Habitats	0.634	0.366	0.634	0.366	0.634	0.366
	Land-use potential			0.500	0.500	0.290	0.710	0.941	0.059
		Noise		0.001	0.999	0.001	0.999	0.001	0.999
		Groundwater		0.030	0.970	0.066	0.934	0.012	0.988
	Pollution	Air		0.500	0.500	0.599	0.401	0.599	0.401
Goal		Soil		0.599	0.401	0.181	0.819	0.954	0.046
	Urban development	Social index		0.168	0.832	0.500	0.500	0.500	0.500
		Territory index		0.195	0.805	0.500	0.500	0.155	0.845
	Hydrologic factors	Floods		0.255	0.755	0.155	0.845	0.155	0.845
		Groundwater supply		0.918	0.082	0.790	0.210	0.790	0.210
		Land movements		0.805	0.195	0.805	0.095	0.805	0.195
	Geologic factor	Regional subsidence		0.988	0.012	0.988	0.012	0.988	0.012
		Faults		0.988	0.012	0.988	0.012	0.988	0.012
	Biologic factors	Species diversity		0.528	0.472	0.516	0.484	0.540	0.460
		Habitat diversity		0.452	0.548	0.395	0.605	0.504	0.496

[a]H1 and T1 correspond to option Hidalgo and option Texcoco for scenario 1, H2 and T2 to scenario 2 and H3 and T3 to scenario 3, respectively.

would not generate significant urban sprawl (hereafter alternatives H1 for Hidalgo and T1 for Texcoco). For scenario 2, the assumption was that the airport would generate significant urban expansion according with state and federal land-use schemes (hereafter alternatives H2 for Hidalgo and T2 for Texcoco). For scenario 3, the assumption was that airport would generate significant urban sprawl, making ineffective government land-use schemes (hereafter alternatives H3 for Hidalgo and T3 for Texcoco).

After the second workshop, some experts noted that the criterion of urban development in hierarchy structure A was redundant because of its correlation with other decision criteria, so hierarchy structure B (Fig. 1b) resulted of the removal of urban development. We then warned the group of experts about the potential biases of the hierarchy structures A and B and encouraged them to carefully review their topologies. In particular, we detected one type of behavioral bias that arises in hierarchically elicited weights (see Lootsma 1999; Pöyhönen and Hämäläinen 1998): The weight of criterion land-use was artificially increased because it was placed higher with respect to the other terminal decision criteria in the hierarchy structure. To prevent such bias, the experts proposed hierarchy structure C (Fig. 1c). Simultaneously, the integration group worked closely with the specialist groups to generate the decision matrix shown in Table 2. Once all the elements of the MCDA were finished, the integration group evaluated the alternatives and performed the sensitivity analyses. The results were presented during the third workshop in a plenary session. After reviewing the character and implications of results, the experts endorsed by consensus the conclusions of the MCDA.

Evaluation of Alternatives

We evaluated the two alternatives under each one of the three scenarios by means of compromise programming or CP (Lootsma 1999; Szidarovszky and others 1986). The distance to the ideal point was considered as a site-suitability index measuring the fitness of each site for the airport (the ideal point is an abstract site possessing the most desirable values of each of the I decision criteria). Formally, the site suitability score, d_j, was computed as the departure from the ideal point (Szidarovszky and others 1986); a scale of 0 (worst) to 1 (best) was used because of its intuitive appeal:

$$d_j = 1 - \left[\sum_{i}^{I} w_i^p \left(\frac{y_i^- - y_{ij}}{y_i^- - y_i^*} \right)^p \right]^{1/p},$$

where w_i is the weight of the i-th decision criterion; y_{ij} is the original value of the i-th decision criterion in the j-th alternative; y^*_i is the best value of the i-th decision criterion; y^-_i is the worst value; and p is the compensation parameter ($p = 1, 2, \infty$).

The term within parenthesis in Equation 1 standardizes y_{ij} into a common value scale with interval properties, y'_{ij}. Because CP identifies alternatives in relation to a distance to an infeasible ideal point (Tecle and others 1998), the best value, y^*_i, was conceptualized as that value producing no impact, whereas the worst value was conceptualized as an impact equivalent to implementing the two alternatives simultaneously, so $y_i^- = \sum_j y_{ij}$. The standardization of the decision criteria resulted in the decision matrix shown in Table 2.

The choice of a particular value of p (called the compensation parameter) in Equation 1 depends on the degree of conflict in the decision process: The greater the conflict between experts or stakeholders, the smaller the possible compensation becomes (Tecle and others 1998). In other words, the compensation parameter p defines the kind of distance metrics used in the analysis and affects the relative contribution of individual deviations from the ideal point, thus leading to different decision-making modes. For $p = 1$, the decision becomes compensatory, meaning that a decrease in the distance to the ideal point in one criterion is compensated by an equivalent increase in another criterion; it corresponds to the original AHP. For $p = 2$, the mode is partially compensatory, meaning that distances to the ideal point of all the criteria can be compensated simultaneously; it corresponds to selecting the alternative with the least defects. For $p = \infty$, the mode is noncompensatory and corresponds to selecting the alternative with the best performance in a single criterion. A detailed discussion on the compensatory parameter p can be found in Zeleny (1974) and Szidarovszky and others (1986).

Sensitivity Analysis

Interval Judgement Analysis. The differences in both information and understanding about the environmental impacts of the airport translated into divergence of judgment in the pairwise comparisons required by the AHP (Table 1). That is, the group of experts could not converge to a single estimate of paired judgments. The lack of convergence denoted uncertainty among the group of experts about the importance weights of the environmental attributes, and hence the rankings of the alternatives could reverse depending on particular combinations of pairwise judgments. Because average weights expressed by a group do not describe individual opinions (Pöyhönen and Hämäläinen 1998), we carried out a stochastic simulation to examine the repercussions of the uncertain judgments in terms of rank-reversal probabilities.

The simulation procedure consisted in replicating n times the possible pairwise comparisons in the judgment matrix (Table 1). This allowed us to empirically derive n eigenvectors (containing the criteria weights). Next, we analyzed the degree of stability of the rankings by means of statistical inference to obtain the confidence intervals and rank reversal probabilities among the decision criteria and the two alternatives. These probability values indicated the stability of the rank ordering of the two alternatives: If the rank reversal probability between two alternatives was high, then a definitive arrangement could not be established, and the rankings were said to be unstable; in contrast, if the rank reversal probability between two alternatives was low, then the highest ranked alternative was indeed preferred, and the rankings were said to be stable (Banuelas and Antony 2004; Hahn 2003; Saaty and Vargas 1987; Van den Honert 1998).

We based the stochastic simulation on the interval judgment procedure described by Saaty and Vargas (1987). The interval judgments ranges shown in Table 1 were used to simulate random pairwise com-

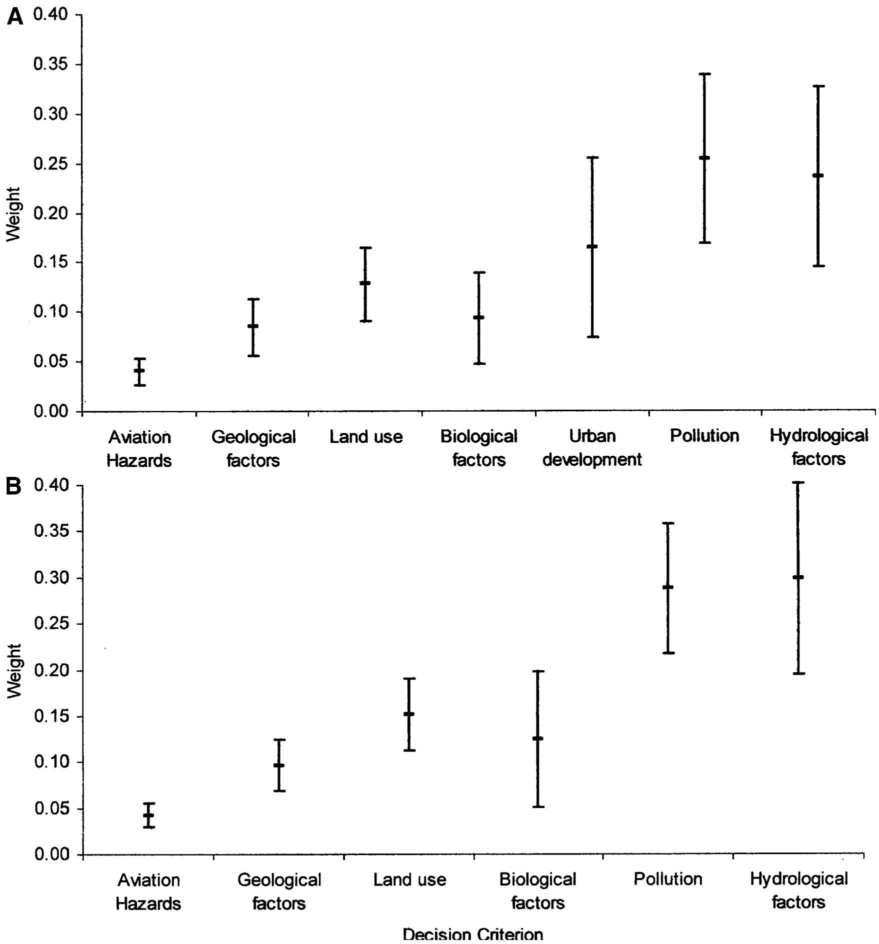

Figure 2. Mean weight (horizontal line) and 99% confidence intervals of decision criteria for the airport environmental assessment. **(a)** Hierarchy structure A. **(b)** Hierarchy structures B and C.

parisons matrices assuming a uniform distribution. The procedure was replicated 30,000 times, discarding those eigenvectors produced by matrices with consistency ratios >0.1 (and thus meeting the consistency condition of AHP; Saaty 1980). This procedure yielded fewer eigenvectors for hierarchy structure A ($n = 468$) than for structures B and C ($n = 1458$). Rank-reversal probabilities amongst the decision criteria weights were estimated using 99% confidence intervals.

Results revealed a high probability ($p > 0.9$) of at least one rank reversal occurring among the decision criteria. For decision criteria at the second hierarchy level in hierarchy structure A, rank reversals probabilities were high ($p > 0.5$) among (1) pollution, hydrological factors, and urban development; (2) hydrological factors, land-use, and urban development; and (3) urban development, land-use, biological factors, and geological factors (Fig. 2a). The elimination of urban development in hierarchy structures B and C resulted in high rank-reversal probabilities ($p > 0.5$) for (1) hydrological factors and pollution; (2) biological factors and land use; and (3) geological factors and biological factors (Fig. 2b).

At the bottom of the hierarchy structure, high rank-reversal probabilities ($p > 0.5$) were obtained for (1) land-use potential, groundwater pollution, groundwater supply, and land-use index; (2) habitat diversity, soil pollution, land movements, floods, species diversity, air pollution, and social index; (3) volcanic eruptions, storms, local subsidence, earthquakes, and geologic faults; and (4) hazardous species, hazardous habitats, noise, and regional subsidence.

Site Suitability Scores. The eigenvectors resulting from the interval judgment analysis were used as inputs in Equation 1, and we then computed the mean suitability score $\bar{d}_j$, and the 99% confidence intervals for each scenario. In general, $\bar{d}_j$ was the highest for H3 and the lowest for T3, whereas $\bar{d}_j$ varied depending on the scenario and the hierarchy structure for the other alternatives.

Rank-reversal probabilities varied depending on the scenario and the decision mode. In general rank-reversal probabilities were higher in the partially com-

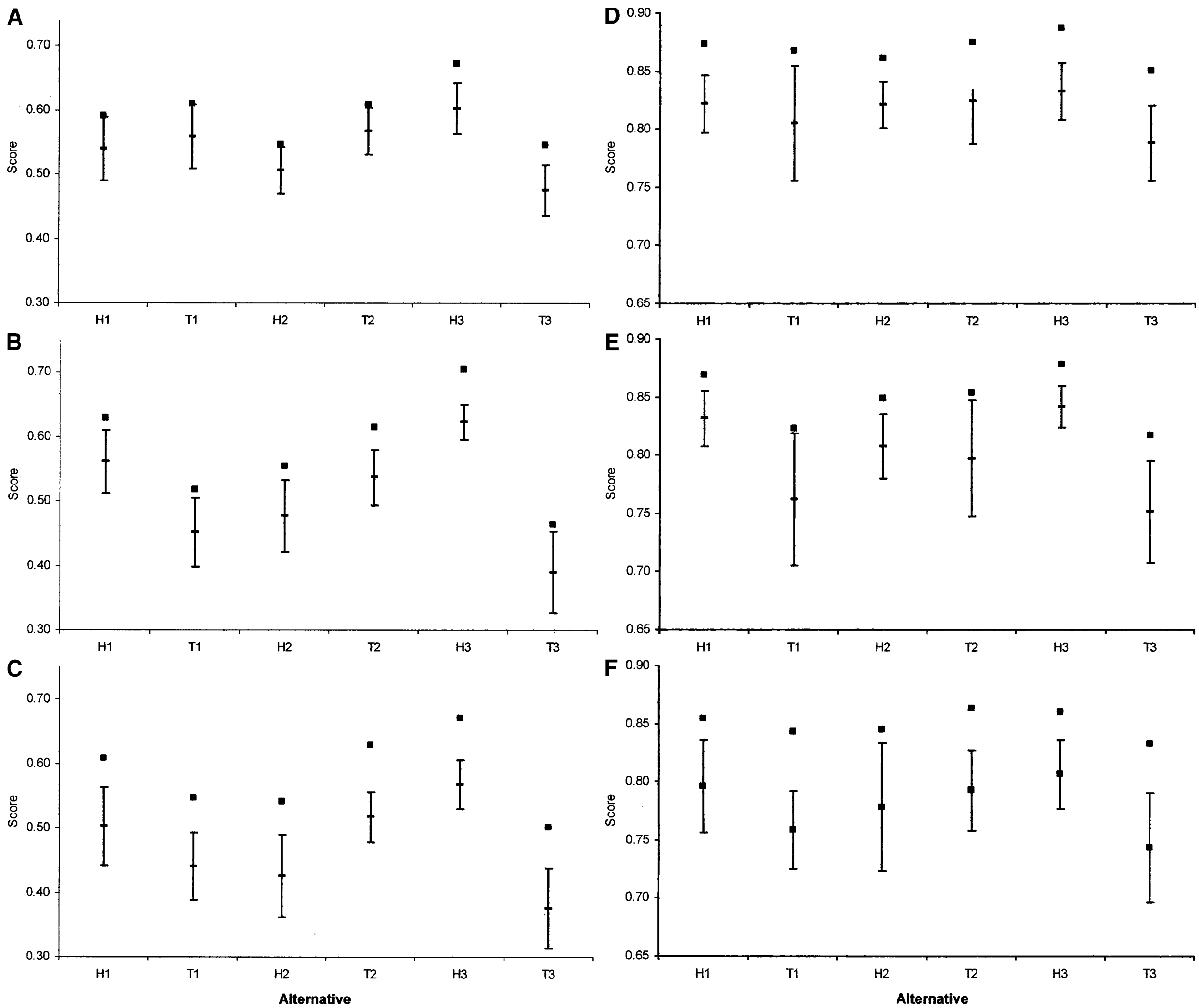

Figure 3. Mean (horizontal line), 99% confidence intervals (vertical lines), and maximized values obtained through Equation 4 (squares) of the suitability scores for the airport environmental assessment using the compensatory decision mode ([A] hierarchy structure A; [B] hierarchy structure B; and [C] hierarchy structure C) and the partially compensatory decision mode [D] hierarchy structure A; [E] hierarchy structure B; and [F] hierarchy structure C. In the abscissa, H1 and T1 correspond to option Hidalgo and option Texcoco for scenario 1, H2 and T2 to scenario 2, and H3 and T3 to scenario 3, respectively.

pensatory mode than in the compensatory mode. More specifically, under the compensatory decision mode (Figs. 3a through c) rank reversals did not occur among alternatives H3–T3 and T2–T3 in the three hierarchy structures or among H1–T3, H3–T1, H1–T1, H3–H2, and H3–T2 in hierarchy structure B. In contrast, rank-reversal probabilities were high ($p > 0.5$) among alternatives H1–T1, H1–H2, T1–H2, and H3–T2 in hierarchy structure A and among T1–H2, T1–T3, and H2–T3 in hierarchy structure C, and they were low ($0.1 \leq p \leq 0.2$) in H2–T2 in hierarchy structure A and among H1–H3, H1–H2, H1–T2, and T1–T2 in hierarchy structure B. Under the partially compensatory mode (Figs. 3d through f), rank reversals did not occur among alternatives H3–T3 and H1–T3 in hierarchy structure B. In contrast, rank-reversal probabilities varied from high to very high ($0.2 \leq p \leq 1$) among all the alternatives in hierarchy structures A and C.

Critical Threshold Analysis. One source of disagreement among the experts and stakeholders was the uncertainty of the decision criteria measurements, y_{ij}, in relation to the ranking of the alternatives. In particular, some of the experts claimed that uncertainty in the measurement of the decision criteria could result in a wrong estimation of the site-suitability scores. Most of the concerns were related to the decision criteria believed to be the most environmentally vulnerable: species diversity, habitat diversity, groundwater supply, groundwater pollution, geological faults, and potential land use.

Direct quantification of the uncertainty in the values of the decision criteria, y_{ij}, was unrealistic under the limitations of the EIA. Instead, we examined the reliability of the standardized measurements, y'_{ij}, using Triantaphyllou's (2000) critical threshold analysis. This analysis required determining the critical threshold, τ_{ijk}, in the amount of y'_{ij} needed to produce a change in the distances to the ideal point, d_j and d_k, so that a rank reversal occurred between alternatives j and k:

$$\tau_{ijk} = \frac{d_j - d_k}{d_j - d_k + w_i(y'_{ik} - y'_{ij} + 1)} \times \frac{100}{y'_{ij}}.$$

Equation 2 was applied to the decision criteria of the three hierarchy structures using the d_j and d_k that resulted from the compensatory decision mode (i.e., using $p = 1$ in Equation 1). We obtained the first quartile of τ_{ijk} and the probability of a threshold event (i.e., $\tau_{ijk} \leq 100\%$) of the total number of cases resulting from the interval judgment ($n = 468$). Hence, the sensitivity of a decision criterion measurement tended to be higher as the probability of τ_{ijk} increased and the first quartile of τ_{ijk} (hereafter called τ_{ijk} threshold) decreased.

The possibility of rank reversals caused by uncertainty in measurement of the criteria was dismissed because all the decision criteria presented high to very high τ_{ijk} values ($\tau_{ijk} \geq 18\%$). In general, thresholds were consistently lower and rank reversal probabilities higher in hierarchy structure A than in hierarchy structures B and C, whereas rank-reversal probability was higher in scenario H1–T1 than in scenarios H2–T2 and H3–T3. Furthermore, a close inspection of the results provided further evidence about the weakness of hierarchy structure A with respect to the other two hierarchy structures. In scenario H1–T1, the lowest critical threshold corresponded to land-use potential in hierarchy structure A ($\tau_{ijk} = 20\%$; $p = 1$). In contrast, the lowest critical threshold corresponded to this same criterion hierarchy structure B at a much higher threshold value ($\tau_{ijk} = 70\%$; $p = 0.75$). The lowest critical threshold corresponded to groundwater pollution in hierarchy structure C with an equivalent value to that of land-use potential in hierarchy structure A but at much lower probability of occurrence ($\tau_{ijk} = 20\%$; $p = 0.05$). In scenario H2–T2, the lowest critical threshold corresponded to land movements in hierarchy structure A ($\tau_{ijk} = 18\%$; $p = 0.12$), whereas the rest of the criteria presented high to very high critical threshold values ($\tau_{ijk} \geq 38\%$; $0.01 \leq p \leq 1$) in the three hierarchy structures. In scenario H3–T3, the lowest critical threshold occurred in hierarchy structure A for territory index with a very low probability ($\tau_{ijk} = 50\%$, $p = 0.01$). Critical thresholds either did not occur or occurred at a very high value and at a very low probability ($\tau_{ijk} \geq 90\%$, $p \leq 0.05$) with the exception of groundwater supply and land-use potential, which presented very high rank thresholds and reversal probabilities ($\tau_{ijk} \geq 80\%$, $p = 1$).

Critical weight analysis. We applied Triantaphyllou's (2000) procedure to identify the critical decision criteria with respect to their weights. This procedure consists in determining the minimum weight change in a decision criterion to produce a rank reversal; thus, the smaller the weight change needed to produce a rank reversal, the more critical a decision criterion was. Accordingly, the minimum change in percentage, δ_{ijk}, needed in w_i such that a rank reversal occurred between alternatives j and k under the compensatory decision mode was found by:

$$\delta_{ijk} = \frac{d_j - d_k}{y'_{ij} - y'_{ik}} \times \frac{100}{w_i}, \quad \forall y'_{jk} > y'_{ik}.$$

Equation 3 was applied to the data sets of the three hierarchical structures. δ_{ijk} was considered possible if the change in a criterion weight did not exceed the corresponding 99% confidence interval. Next, the median δ_{ijk} and the probability of occurrence of δ_{ijk} events of the total number of cases resulting from the interval judgment analysis ($n = 468$ for hierarchy structure A and $n = 1458$ for hierarchy structures B and C) were obtained for each decision criterion. Hence, the sensitivity of a decision criterion weight tended to be higher as the probability of δ_{ijk} increased and the median δ_{ijk} (hereafter called δ_{ijk}) decreased.

Five critical criteria were identified: groundwater supply, groundwater pollution, floods, regional subsidence, and land movements; changes in the rest of the criteria could not produce rank reversals. However, the sensitivity of the rankings to changes in the weight of these criteria varied between scenarios and hierarchy structures. For rank reversals involving H1–T1, the rank-reversal probabilities were higher and the changes in weights smaller in hierarchy structure A ($2\% \leq \delta_{ijk} \leq 6\%$; $0.14 \leq p \leq 0.75$) than in hierarchy structures B and C ($13\% \leq \delta_{ijk} \leq 33\%$; $0.02 \leq p \leq 0.55$). For rank reversals involving H2–T2, critical weight sensitivity was similar to that observed for hierarchy structures B and C from the previous scenario ($12\% \leq \delta_{ijk} \leq 25\%$; $0.07 \leq p \leq 0.33$), whereas for rank reversals involving H3–T3, critical weight sensitivity was negligible ($29\% \leq \delta_{ijk} \leq 63\%$; $p \leq 0.002$).

Optimal Weigh-Set Analysis. Anderson and others (2001) stressed the importance of appraising the sensitivity of alternative rankings to different possible combinations of weights within their confidence intervals. Hence, we searched for an optimal combination of weights that maximized the site suitability score and then compared this maximized score with the top value of the corresponding confidence interval. If the maximized score was not higher than the top value, the reliability of the results increased; otherwise, we checked for possible rank reversals.

The optimization problem was implemented through linear programming by means of the utility Solver in the spreadsheet Excel using as constraints the 99% confidence intervals of each criterion weight. Accordingly:

$$1 - \left[\sum_{i}^{I} \beta_i^p \left(\frac{y_i^- - y_{ij}}{y_i^- - y_i^*}\right)^p\right]^{1/p} > 1 - \left[\sum_{i}^{I} w_i^p \left(\frac{y_i^- - y_{ij}}{y_i^- - y_i^*}\right)^p\right]^{1/p},$$

subject to:

$$\begin{gathered}\sum_{i}^{I} \beta_i = 1 \\ \beta_i \in C_i\end{gathered},$$

where C_i is the 99% confidence interval for w_i; the left hand side of the inequality is the maximized suitability score, d_{max}, and the right hand side is the value, d_j, for the upper confidence limit of suitability scores for alternative j; and β_i is the weight of the i-th decision criterion that results in d_{max}.

The only consequential result of this analysis for the EIA was that of the partially compensatory mode (Fig. 3f): the maximized site-suitability scores implied that T2 > H3 in hierarchy structure C, reversing the overall pattern of H3 as the top-ranked alternative. For the rest of the cases, we concluded that results were reliable because either the maximized site-suitability scores matched the upper limit of the respective confidence intervals (as in the case of scenarios H1–T1 and H2–T2 for the compensatory decision mode), or the maximized site-suitability scores preserved the rankings (Fig. 3a through f).

Discussion and Conclusions

Results showed that neither option Hidalgo nor option Texcoco prevailed in terms of their environmental suitability for the airport. Unsurprisingly, the government of Hidalgo rebuked this conclusion, confirming the insightful remark by Beattie (1995) that EIAs are always political. In this highly politicized process, the sensitivity analysis turned out to be fundamental for building consensus on the critical environmental issues and the prevention measures to be implemented before the execution of the airport project at either site. Thus, the politically motivated objections to the EIA did not last in face of the comprehensiveness, transparency, and rigor of the MCDA.

In retrospect, the conclusion of the EIA seems reasonable because, as stated by Rowe and Pierce (1982), identifying an obviously dominant alternative is unlikely at the last stages of a sitting process, as was indeed the case of the airport. It is also interesting to point out that the implementation of the MCDA for this case study resembles the experience of Keeney and Raiffa (1976), even though the sociopolitical context and the alternatives considered differed. These investigators found that the partakers were initially ''very surprised and bewildered'' when confronted with the results of the analysis, but they adopted a more sensible attitude later on as they understood the implications better. From another perspective, our case study also substantiates Lavelles and others' (1997) argument on the importance of a systematic consideration of the inherent uncertainty of MCDA. In that respect, the present case study extends these investigators' analyses to the context of environmental conflict resolution.

This case study pinpoints some key elements of MCDA implementations for controversial infrastructure projects. First, simple MCDA implementation should be avoided in a complex EIA. This apparent truism is nevertheless necessary given that most practitioners rely on rather straightforward MCDA applications (Beinat 2001). As our results show, carrying out the original AHP could have led to flawed decision making and perhaps to the exacerbation of conflict in the airport case. For example, suppose that by chance a group of experts applies the original AHP based on hierarchy structure B under the compensatory mode in CP (Fig. 3b). Then, one would have to conclude that (1) if the land-use restrictions were strictly enforced, then the decision would be indifferent to the two sites (H2 = T2); (2) if the urban sprawl were unchecked, then option Hidalgo should be preferred (H1 > T1 and H2 > T3); and (3) given that the experts' judgments produce the optimal weights, the top-ranked alternative would correspond to option Hidalgo with unchecked urban sprawl (H3 > H1 > T2 > H2 > T1 > T3). In contrast, suppose now that another group of experts arrives to hierarchy structure C and applies CP in the partially compensatory mode (Fig. 3f). One would have to conclude that: (1) the site-suitability scores between the alternatives were not significantly different, and (2) according to the results of the implementation of Equation 4, option Texcoco following government land-use planning would be the top-ranked alternative (T2 > H3 > H1 > T1 > H2 > T3).

These examples highlight the need for a combination of stochastic AHP and sensitivity analysis to explore the consequences of different hierarchy structures and decision modes in the alternative rankings. Using this approach, we were able to address the typical issues of a complex and controversial EIA (i.e., subjective, biased, and value-laden judgments) in a systematic and comprehensive way.

In the case of the airport, the information for the assessment was readily available. The experts' role was to gather the relevant information and interpret it in terms of decision criteria. However, there may be cases in which cardinal scales may be difficult to appraise, and experts may prefer to articulate their evaluations in ordinal scales based on qualitative information. A MCDA approach that could be implemented in such cases is the stochastic multicriteria acceptability analysis (Lahdelma and others 2003).

Second, in controversial projects, one should expect instability in the ranking of alternatives arising from divergences of judgment and uncertainties in the performance of decision criteria. Instability in the rankings precludes unanimous support whenever the final aggregated scores are similar among the alternatives. Therefore, an essential component of MCDA implementations for EIA is a comprehensive sensitivity analysis.

In our case, divergence of judgment was manifested in the interval judgment matrix (Table 1) and the three hierarchy structures (Figs. 1a through c), whereas uncertainty in criteria performance resulted not only from of the ability to predict the real value of the environmental attributes but also from the assumptions involved in each scenario. With respect to the divergence of judgment, our results provide evidence for the assertion by Arbel (1989) and Van den Honert (1998) on the advantages of examining the effects of lack of unanimity in a comparison matrix to achieve consensus in an MCDA. In fact, the interval judgment approach promoted dialogue among the experts throughout the EIA; it actually focused the argumentation on possible ranges of the pairwise comparisons rather than forcing the experts to agree on a single number taken from Saaty's comparison scale. This allowed the experts to get an appreciation for the effects of their disagreement on the final rankings, which facilitated consensus on the final results.

Regarding the three hierarchy structures, the sensitivity analysis allowed us to settle discussions related to the correlation problem of urban development with other decision criteria. In addressing this issue, hierarchy structure C proved to be the most appropriate for depicting the environmental impacts of the airport because it presented the lowest rank reversal sensitivity to weight uncertainty and measurement errors of the decision criteria. In this way, it was evident for the experts that the robustness of decisions based on the AHP depends on both the distribution and relative weights of the decision criteria in a hierarchy structure. In other words, hierarchy structure C decreased the behavior bias produced by criterion land-use in hierarchy structures A and B (see Lootsma 1999; Pöyhönen and Hämäläinen 1998). In addition, a comparison among hierarchy structures B and C adds to Paulson and Zahir's (1995) remark that ranking uncertainty decreases as the depth of the hierarchy increases.

The optimal weight set analysis revealed a logical inconsistency in the EIA with respect to a general trend of H3 being the top-ranked alternative (recall that H3 means building the airport in option Hidalgo, assuming that urban sprawl would remain unchecked). Surprisingly, the experts were not fully aware of such inconsistency before the sensitivity analysis. Perhaps the complexity of the problem prevented them from recognizing it earlier in the assessment. The inconsistency was revealed when the maximized site-suitability scores under hierarchy structure C and the partially compensatory mode showed that T2 > H3 (Fig. 3f).

In addition to contributing to a more cogent EIA, results of both the critical threshold and the critical weight analyses were also helpful in settling arguments about criteria called into question by some stakeholders. With respect to critical thresholds, for example, conservation advocacy organizations claimed that the number of affected species considered in our analysis was underestimated in favor of option Texcoco. In confrontational circumstances such as those of the airport, settling the ''right'' number of species could result in endless debate. Hence, instead of arguing, we found from the critical threshold analysis that an increase of at least 40% in the number of species would be needed to invalidate our conclusions: an impossible increase.

In a similar way, the critical weight analysis helped us to explain in more detail the reasons behind the EIA conclusions. This analysis identified groundwater supply and groundwater pollution as the key sources of uncertainty in the EIA. They were critical because of their comparatively high importance weights and the relatively wide confidence intervals of hydrological factors and pollution (Fig. 2). In addition, groundwater supply and groundwater pollution had contrasting values in the two alternatives (see Table 2), thus making it impossible to discern either option Hidalgo or option Texcoco as the best site for the airport. These findings about the reliability of the EIA were very persuasive for stakeholders and partakers.

Third, it is important for users of MCDA to recognize that group decision making using this technique involves a process with a relatively steep learning curve for the disciplinary experts involved. Initial lack of experience with MCDA may incite unconstructive debates among the experts involved in an EIA. Although we agree in principle with Ramanathan's (2001) conclusion that the AHP simplifies the otherwise painstaking process of identifying and understanding the critical factors in an EIA, implementing the AHP for the airport was challenging because most of the experts were unfamiliar with MCDA techniques. We actually faced a negative attitude from some experts similar to those observed by Janssen (2001) at the beginning of the study. As a matter of fact, the software Expert Choice (Windows version 9.0: Software, Mcheau, VA), although practical during the workshops, engendered apprehension and rejection in some instances, inasmuch as it was perceived as a ''black box.'' Furthermore, the experts perceived the AHP as prone to manipulation, too technocratic, and deceptive. Specifically, they had reservations about the development of hierarchy structures, the validity of the pairwise comparisons, and the standardization procedure.

However, the experts' initial reservations to MCDA could have worsened during the assessment had it not been for the iterative scheme in which the EIA was implemented. Stumpf and Freedman's (1979) asserted that designing effective interdisciplinary undertakings requires careful consideration of the decision-making context and the experts' backgrounds and temperaments. Accordingly, the iterative scheme in which the MCDA was implemented allowed the experts to progressively gain a better understanding of the repercussion of their judgments on the final rankings. Eventually, that understanding translated into consensus among the experts about the results of the assessment and greater confidence in MCDA.

Our results support Tran's and others (2002) assertion that MCDA provides a framework for moving from environmental judgment to decision-making. In all, this case study confirms previous observations (e.g., Bana e Costa 2001; Janssen 2001; Munda 2003) of the advantages of MCDA for environmental planning and management. In practical terms, the advantage of our MCDA implementation was that it allowed each member of the interdisciplinary team to decipher his or her understanding about the environmental impacts of the new airport. Paraphrasing Van den Honert (1998), this case study emphasizes the need for determining the range of inputs for which a particular decision holds so that consensus can be attained.

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