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Multicriteria Planning of Post-Earthquake Sustainable Reconstruction

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Abstract: *A multicriteria model is developed for analyzing the planning strategies for reducing the future social and economic costs in the area with potential natural hazard. The developed multicriteria decision-making procedure consists of generating alternatives, establishing criteria, assessment of criteria weights, and application of the compromise ranking method (VIKOR). The alternatives are the scenarios of sustainable hazard effects mitigation, generated in the form of comprehensive reconstruction plans, including the redevelopment of urban areas and infrastructures, multipurpose land use, and restrictions on building in hazardous areas. The plans have to be evaluated according to the criteria representing public safety, sustainability, social environment, natural environment, economy, culture, and politics. The multicriteria model can treat all relevant conflicting effects and impacts in their representative units. The evaluation of alternatives is implicated with imprecision (or uncertainty) of established criteria, and the fuzzy multicriteria model is developed to deal with "qualitative" (unquantifiable or linguistic) or incomplete information. The application of this model is illustrated with the post-earthquake reconstruction problem in Central Taiwan, including the restoration concerning the safe and serviceable operation of "lifeline" systems, such as electricity, water, and transportation networks, immediately after a severe earthquake.*

1 INTRODUCTION

The costs of natural hazards are very high and are expected to keep rising. For instance, Japan's 1995 Kobe earthquake was the world's most costly natural disaster (Horikiri and Odani, 1999); $100 billion was estimated to be lost, and 5300 people were killed. The "921" earthquake in 1999 in Taiwan and the 1994 Northridge earthquake in California were significant as well, costing $57 billion (killing 2400) and $20 billion (killing 57), respectively. Mileti considered the reassessment of natural hazards in the United States (1999), and he concluded that "natural hazards response requires a new approach," because, in some cases, steps taken to reduce the impact of natural hazards may actually make the situation worse when more extreme disasters occur. The main objective of many studies was to construct land use, development, or spatial location models that describe or predict the geographical distribution of industry, business, and residential population throughout an urban area. However, in this paper we are developing a model for

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planning the redistribution of industry and residential population throughout the area affected by an earthquake. Post-earthquake restoration and reconstruction are considered as short-term and long-term planning processes, respectively. A long-term solution provides "control corridor" for short-term planning. Kozin and Zhou (1988) considered the safe and serviceable operation of "lifeline" systems, such as gas, electricity, oil, water, communication, and transportation networks, immediately after a severe earthquake. They considered the application of dynamic programming, but with the assumption that all resources can be expressed in a common unit, such as monetary units, although it is not always realistic. Economic measures have much to do with assessing performance of a comprehensive reconstruction plan, but other performance dimensions (such as social, political, and environmental) are also important. Natural hazards mitigation planning is a multicriteria task, involving the public, different agencies, and levels of government. The planning goal is to compromise competitive land uses through the choice of the best combination of uses and to coordinate mutual responsibilities of different agencies and levels of government concerned with the natural resources. With the right (compromised) sustainable reconstruction plan, local government can reduce disaster losses and increase community sustainability.

Multicriteria decision making (MCDM) is considered as a complex and dynamic process in which one managerial level and one engineering level can be distinguished (Duckstein and Opricovic, 1980). The managerial level defines the goals and chooses the final "optimal" alternative; the multicriteria nature of decisions is emphasized at this level, at which public officials called "decision makers" have the power to accept or reject the solution proposed by the engineering level. The decision makers, who provide the preference structure, are "offline" of the optimization procedure done at the engineering level. Very often, the preference structure is based on political rather than solely on technical criteria. In such cases, a system analyst can aid the decision-making process by making a comprehensive analysis and by listing the important properties of noninferior and/or compromise solutions.

The developed multicriteria decision-making procedure consists of generating alternatives, establishing criteria, assessment of criteria weights, and application of the compromise ranking method (VIKOR) that is summarized in section 5.2 and fully described in the book by Opricovic (1998). The alternatives are the scenarios of sustainable hazard effects mitigation, generated in the form of comprehensive reconstruction plans. The alternative plans should consider the redevelopment of urban areas and infrastructures, multipurpose land use, and restrictions on building in hazardous areas. The plans have to be evaluated according to criteria representing public safety, sustainability, social environment, natural environment, economy, culture, and politics.

Imprecision in MCDM can be modeled using *fuzzy* set theory to define attributes and the importance of attributes. According to Bellman and Zadeh (1970), "much of the decision-making in the real world takes place in an environment in which the goals, the constraints, and the consequences of possible actions are not known precisely." The paper by Ribeiro (1996) provides an overview of the concepts and theories of decision making in a fuzzy environment. In a fuzzy environment, criteria and weights all could be fuzzy sets (Teng and Tzeng, 1996). Von Altrock (1995) explains the elements of fuzzy logic system design, presenting case studies of real-world applications. The most visible applications are in the realms of consumer products, intelligent control, and industrial systems. Less visible, but of growing importance, are applications relating to decision support systems. Although fuzzy logic has been and still is controversial to some extent, its successes are too obvious to be denied. But Ribeiro (1996) warns that "too much fuzzification does not imply better modeling of reality; it can be counterproductive."

An application of the fuzzy multicriteria model, developed in this paper, is illustrated with the post-earthquake reconstruction problem in Central Taiwan, considering different scenarios of reconstructing urban areas and infrastructures. Long-term reconstruction projects for earthquake-affected areas are needed to provide data for evaluation of alternative development plans. Due to the lack of original data, the data from the literature is used as supplementary information. A very useful source of information is the paper by Horikiri and Odani (1999), in which the analysis of residents' evacuation behavior after the Kobe earthquake is considered. A part of that information is cited here:

> Over 120,000 buildings collapsed, lifeline facilities (electricity, water, gas supply, etc) were destroyed, and transportation networks were paralyzed. More than 230,000 residents were forced to evacuate immediately after the earthquake. Three years later, the average ratio of reconstructed buildings to the total number of structures that had collapsed was 45% . The study was done for smaller areas. The data used in the study was obtained as a part of the questionnaire survey conducted 3 years after the earthquake. The study area in Kobe City was 3.1 km^2, with population of 53,710. In this area, 54% of the total number of buildings were damaged. Electric supply and telephone service recovered in 2 weeks, but gas and water supplies resumed after 3 months. The population of the study area decreased steeply during the

4 months, and then continued to decrease gradually to 83.6% after 16 months, then it began to increase slightly, but it still stood at 88.2% of the initial level. More than 3,000 buildings (50%) were removed in the 6 months after the disaster. Three years after, the ratio of reconstructed structures was 59%; 1,212 lots were vacant, more than 30% of the total number of removed buildings. Factors contributing to the end of evacuation were the recovery of the lifeline facilities and the reconstruction of damaged buildings (Horikiri and Odani, 1999).

2 GENERATING ALTERNATIVES

The alternatives are the scenarios of sustainable hazard effects mitigation, generated in the form of comprehensive reconstruction plans. The alternative plans should consider the redevelopment of urban areas and infrastructures, multipurpose land use, and restrictions on building in hazardous areas. Generating alternatives may be a very complex process, because there is no general procedure or model, and no mathematical procedure could replace the human creativity in generating alternatives. Simulation and optimization models are used within a heuristic approach in system analysis when human experts have a main role and responsibility in generating alternatives. The set of alternatives has to be complete, and there should be at least one alternative for each aspect and point of view. The final solution will be one alternative from the given set.

The impacts and effects of an earthquake depend on many variables, such as magnitude and duration, population density and distribution characteristics, land use patterns, construction techniques, geological configuration, vulnerability of public supply systems (energy, water, transportation, communication), and long-term physical, social, and economic recovery policies. Various scenarios of hypothetical earthquake disasters for the affected area could be written to show the extent of future disasters. Alternative reconstruction plans are generated with different scenarios, and varying "system parameters" ($s_1, s_2, \ldots$). The following parameters may be considered: s_1, location (epicenter); s_2, magnitude; s_3, probability; s_4, number of reallocated settlements; s_5, land use types; s_6, development regulations; s_7, fiscal policies; s_8, construction techniques. The first three parameters are determined from seismic data for the considered area. All other parameters are related to the regional planning and designing alternatives.

The main optimization goal and the area under consideration have to be the same in all alternatives. The considered area consists of a number of subareas that are geographically formed with some specific characteristics, such as industry, residential, business, military, and human-made reservoirs. Thus, each subarea has a different economic and social importance, and involves a particular subproblem of reconstruction planning.

The hazardous areas do not have to be used more intensively for communities to realize economic objectives, and the development of forestry, agriculture, hydropower, and different reconstruction scenarios have to be considered. Here it should be noted that river basins are the most appropriate geographical units for planning the use of natural resources (Duckstein and Opricovic, 1980). Local government has many land use management instruments, such as building standards, development regulations, land and property acquisition, taxation, and fiscal policies. The community should consider and adopt restrictions on building in hazardous area. A good land use plan helps educate the public.

3 ESTABLISHING CRITERIA

The main aim of a multicriteria approach is to capture all relevant foreseeable impacts in their most appropriate and representative units. In post-earthquake reconstruction planning, the criteria should represent public safety, sustainability, social environment, natural environment, economy, culture, and politics. There are eight criteria defined in this paper. The criteria are established in general, and they are described as follows:

f_1—*Reconstruction costs* (fuzzy or crisp numbers, in USD). This criterion represents reconstruction costs for all buildings and infrastructures within the considered area.

f_2—*Gross domestic production* (crisp or fuzzy numbers, in USD). The GDP has to be determined for all alternatives plans for the considered area.

f_3—*Destroyed houses and apartments* (fuzzy or crisp numbers). The number of potentially destroyed houses and apartments could be determined by the experts, for all alternative plans.

f_4—*Damaged houses* (fuzzy or crisp numbers). For each generated alternative the number of potentially damaged houses has to be determined by the experts.

f_5—*Restoration ability* (crisp or fuzzy numbers). The goal of this study includes the evaluation of seismic performance of "lifeline" systems (energy, water, transportation, and communication) and the measures for mitigating the social risk arising from their failures. The evaluation of these systems is done for each alternative, in terms of duration of restoration.

f_6—*Sustainability* (linguistic variables). A sustainable reconstruction plan requires consideration of the interaction of a planned system (an alternative) with nature and society under present and long-term future conditions. It requires prediction of possible future changes in all variables relevant to the plan (e.g., seismic and ecological conditions) as well as socio-economic conditions, including a potential change in society's value system. The more flexible alternative in the sense of adaptability to future conditions is evaluated as the better one.

f_7—*Acceptability by the local public* (linguistic variables). There is a high motive for public participation in the post-earthquake land use planning, and the public hearing is a practical way of assessing local preference for multicriteria decision making. The acceptability of each alternative could be expressed as a linguistic variable (very good, good, medium, bad, and very bad).

f_8—*Government preference* (linguistic variables). This criterion represents preference of local and state governments. The alternative is evaluated as a better one if there is no conflict between local and global preference.

The set of criteria has to be discussed and accepted by the experts and by the local government. The above set of criteria could be modified to a particular decision-making problem.

The relative importance of each criterion is expressed by weight. The weights in MCDM do not have a clear economic significance, but the use of weights provides the opportunity for modeling the real aspects of decision making (the preference structure). The use of scaling methods to define the weights of the criteria greatly simplifies the mathematics of the weighted average formula without losing any meaning (Ribeiro, 1996). "Equal importance" weights ($w_i = 1/n$) should be used either when there is no information from the decision maker (DM) or when there is not enough information to differentiate the relative importance of criteria. Within an entropy context this case represents total ignorance about criteria preferences. "Given" weights should be used when the DM has a good knowledge about criteria, in terms of their values and of their relationships. Very often, it is not easy to get the values of weights; therefore, rationalizing and using proven elicitation techniques to help the DM express his preference is an important aspect of multicriteria decision making. The preference stability analysis (by VIKOR) could help in perceiving the influence of weights on the proposed (compromise) solution.

4 EVALUATION OF THE ALTERNATIVES

The evaluation of alternatives should be performed according to each criterion from the set of established criteria. The criterion functions could be expressed in the form of different measures and in different units, such as quantitative economic indices (monetary units), quantitative engineering measures (kg, sec, m), and qualitative indices (grades or scores). "Quantitative" evaluations are performed using economic methods and models and engineering methods and measurements. "Qualitative" evaluations are performed by the experts (subjectively). A systematic way to perceive the entire set of criteria is to establish the hierarchy of goal, objectives, criteria, and of all evaluation measures.

Long-term reconstruction projects for earthquake-affected areas are needed to provide data for evaluation of alternative development plans. The local county government is a decision maker within this multicriteria decision making for regional reconstruction and development.

The values of criterion functions can be crisp, linguistic, and/or fuzzy. We assume that many criterion functions are crisp (in nature), their values are determined by economic instruments, mathematical model, and/or by measuring in engineering. Such data should be expressed in original units, and such real data should never be represented in any fuzzy format. However, there are situations when evaluation could not be precise.

Statements using subjective categories (good, fair, and bad) play a major role in the decision-making process of humans. Although the linguistic variables do not have quantitative contents, human can use them successfully for the evaluations. Abstraction and thinking in analogies are possible by the flexibility of human logic. The use of fuzzy sets defined by membership functions in logical expressions is called "fuzzy logic." Fuzzy logic has been developed as a mathematical model to implement the human logic in engineering solutions; but, the full scope of human thinking cannot be mimicked by fuzzy logic (von Altrock, 1995).

5 MULTICRITERIA OPTIMIZATION

5.1 Fuzzy multicriteria model

The multicriteria model can treat all relevant conflicting affects and impacts in their representative units. The evaluation of alternatives is implicated with imprecision (or uncertainty) of established criteria, and the development of a fuzzy multicriteria model is necessary, to deal with "qualitative" (unquantifiable or linguistic) or incomplete information.

To express an imprecise value, as "about m" ("approximately m"), the fuzzy number is used ($\widetilde{N}$), associated with a membership function. The membership function $\mu_{\widetilde{N}}(x)$ denotes the degree of truth that the fuzzy value is equal to x, within the real interval $[l, r]$. One could find out more about the definition of fuzzy numbers, such as triangular numbers, trapezoidal numbers, L-R fuzzy numbers ("nonlinear"), and their arithmetic operations in the abundant literature. The process "fuzzification" uses fuzzy sets for translating real variables into fuzzy or linguistic variables. The "defuzzification" procedure translates the fuzzy result into a real value (crisp). Over-fuzzification can create unnecessary complexity. The fuzzy ranking methods have been developed that can be used to compare fuzzy numbers, but none of the existing methods is perfect (Chen and Hwang, 1992).

The *fuzzy multicriteria optimization* (FUMCO) method is developed to solve the following problem

$$\underset{a \in A}{mco}(f_1(a), f_2(a), \dots, f_n(a))$$

where A is the set of feasible solutions; $a = (s_1, s_2, \dots)$ is the alternative obtained (generated) with certain values of system variables (s); f_i represents i-th criterion; *mco* denotes the multicriteria optimization operator.

The FUMCO method, developed in this paper, consists of two phases of solving the fuzzy multicriteria problem, as follows.

CFU phase: converting the fuzzy data into crisp scores. The results of the *CFU* phase are the crisp data for *MCO* phase;

MCO phase: multicriteria optimization using the compromise ranking method.

Fuzzy data within the FUMCO model may be expressed in linguistic terms or as fuzzy numbers. Linguistic variables are converted using conversion scales. In this paper, the conversion direct into crisp numbers is proposed. For example, linguistic variables: low, medium, and high, are converted into 0, 0.5, and 1, respectively. The conversion scaling could be a nonlinear function or any mapping with the results as crisp numbers.

The second procedure within *CFU* phase is converting fuzzy numbers into crisp scores ("defuzzification"). Suppose that the alternatives are evaluated according to i-th criterion with the fuzzy numbers $\tilde{f}_{ij}$, $j = 1, \dots, J$ (J is the number of alternatives). The corresponding fuzzy scores are determined as real (crisp) numbers by the procedure similar to "Converting Fuzzy Numbers to Crisp Scores" proposed by Chen and Hwang (1992, pp. 474–6). For the triangular fuzzy number $\tilde{f}_{ij} = (l_{ij}, m_{ij}, r_{ij})$, the real value of i-th criterion function could be determined by the following equation:

$$f_{ij} = \frac{r_i^{\max}}{2}\left(\frac{r_{ij}}{r_i^{\max} + r_{ij} - m_{ij}} + \frac{m_{ij}}{r_i^{\max} + m_{ij} - l_{ij}}\right) \quad (1)$$

where $r_i^{\max} = \max_j r_{ij}$.

According to Equation (1): $f_{ij} > m_{ij}$ if $m_{ij} < r_i^{\max}/2$; and $f_{ij} \le m_{ij}$ if $m_{ij} \ge r_i^{\max}/2$. Chen and Hwang (1992) considered the assumption that human intuition would choose a fuzzy number (symmetrical triangular) that has higher mean (m) and a smaller spread b ($b = r - m = m - l$), supposing that the criterion function has to be maximized. The above conversion procedure (1) includes this assumption only for $m > r^{\max}/2$, but for $m < r^{\max}/2$ the fuzzy number with larger spread (b), and same m, has higher real value f_{ij}. This indicates that there is a tendency to the middle of the scale ("risk-aversion" procedure).

Applying the *CFU* phase of the FUMCO algorithm, the performance matrix with fuzzy elements $\tilde{f}_{ij}$, (l_{ij}, m_{ij}, r_{ij}), $j = 1, \dots, J$, is transformed into one with real numbers ($f_{ij}, j = 1, \dots, J, i = 1, \dots, n$), and an existing MCDM method (classical) can be used.

5.2 Compromise solution

Practical problems are often characterized by several noncommensurable and conflicting criteria, and there is no solution satisfying all criteria simultaneously. The compromise solution of the problem with conflicting criteria should be determined. The compromise ranking method (known as VIKOR) is introduced as one applicable technique to implement within MCDM (Opricovic, 1998). In this paper, the main feature of this method is presented. Assuming that each alternative is evaluated according to each criterion function, the compromise ranking is performed by comparing the measure of closeness to the ideal alternative. The multicriteria merit for compromise ranking is developed from the L_p*-metric* used in compromise programming method (Zeleny, 1982; Yu, 1989). The various alternatives are denoted as $a_1, a_2, \dots, a_J$. For an alternative a_j the merit of i-th aspect is denoted by f_{ij}, that is, f_{ij} is the value of i-th criterion function for the alternative a_j; n is the number of criteria.

The compromise ranking algorithm (VIKOR) consists of sorting the alternatives according to the values S, R, and Q, formulated as follows:

$$S_j = \sum_{i=1}^{n} w_i (f_i^* - f_{ij})/(f_i^* - f_i^-)$$

$$R_j = \max_i \left[w_i (f_i^* - f_{ij})/(f_i^* - f_i^-)\right]$$

$$Q_j = v(S_j - S^*)/(S^- - S^*) + (1 - v)(R_j - R^*)/(R^- - R^*)$$

where $f_i^* = best_j f_{ij}$, $f_i^- = worst_j f_{ij}$; $S^* = \min_j S_j$, $S^- = \max_j S_j$, $R^* = \min_j R_j$, $R^- = \max_j R_j$; w_i are the weights of criteria; v is introduced as a weight of the decision-making strategy of "the majority of criteria" (or "the maximum group utility"), usually $v = 0.5$. The VIKOR algorithm proposes as a compromise solution, for given criteria weights, the alternative (a'), which is the best ranked by the measure Q if the following two conditions are satisfied:

$C1$. *"Acceptable advantage"*: when $Q(a'') - Q(a') \ge DQ$; where a'' is the alternative with second position in the ranking list by Q; $DQ = 1/(J - 1)$ ($DQ = 0.25$ if $J \le 4$) J is the number of alternatives.

$C2$. *"Acceptable stability in decision making"*: The alternative a' has also to be the best ranked by S or by R, or by both, as well. This compromise solution is stable within the decision-making process, which could be: "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$).

If one of the conditions is not satisfied, then the set of compromise solutions is proposed, which consists of:

- Alternatives a' and a'' if only the conditions C2 is not satisfied;
- Alternatives $a', a'', \ldots, a^{(k)}$ if the conditions C1 is not satisfied; $a^{(k)}$ is determined by the relation $Q(a^{(k)}) - Q(a') \approx DQ$ (the positions of these alternatives are "in closeness").

By the compromise ranking method, the compromise solution is determined, which could be accepted by the decision makers because it provides a maximum "group utility" of the "majority" (with measure S, representing "concordance"), and a minimum of the individual regret of the "opponent" (with measure R, representing "discordance"). The VIKOR algorithm determines the weight stability intervals for the obtained compromise solution with the "input" weights, given by the experts (Opricovic, 1998).

6 ILLUSTRATIVE EXAMPLES

6.1 Ranking of the districts according to the damages

Long-term reconstruction projects for earthquake-affected areas are needed to provide data for evaluation of alternative development plans. Due to the lack of original data, the data from the literature are used as supplementary information (Horikiri and Odani, 1999). A very useful source of information are the papers (and Web pages) published by the Academia Sinica, Taiwan. The "921" (Chichi or Jiji) earthquake in Central Taiwan in 1999 had a magnitude of $M_L = 7.3$. The epicenter was located at 23.85°N, 120.81°E in Nantou County. In this area there are five main faults indicating the potential earthquakes and making the regional planning a more difficult task (Figure 1).

The data about damages (from Web page) caused by the "921" earthquake are presented in Table 1. Taichung City is 38 km NNW from the "921" epicenter, Wufeng in Taichung County is 29 km NNW, and Nantou City is 16 km NW distant.

The data from "local source" in Nantou County are presented in Table 2. The difference between the data in Table 1 and Table 2 is obvious.

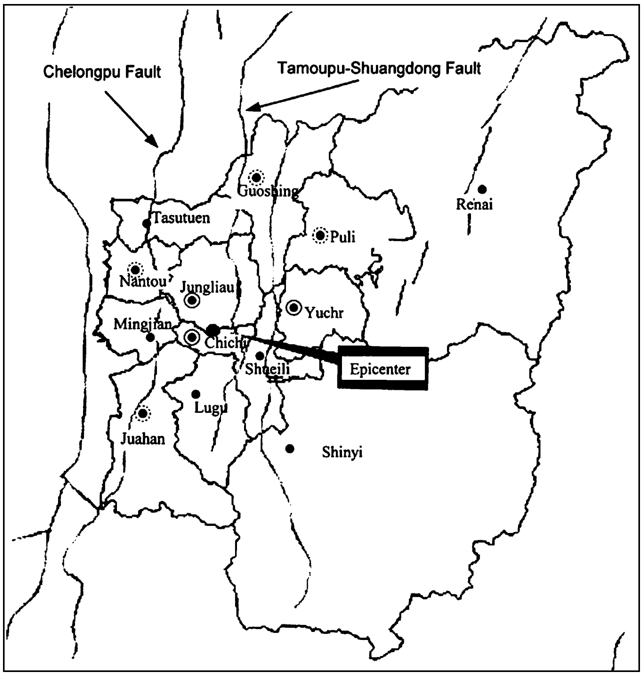

Fig. 1. Nantou County—faults and districts.

Interesting results are obtained by factor (statistical) analysis. Chichi, Jungliau, and Yuchr are included in the same factor (using "Rel" data). The high correlation is found between the following pairs of variables:

- number of collapsed houses and number of damaged houses (with "Abs" and "Rel" data)
- number of severely injured and number of collapsed houses (with "Abs" and "Rel" data)
- number of damaged houses and number of population (with "Abs" data)

The correlation is very low between the distance from the epicenter and each variable ("Abs" value) from Table 2; this distance is only correlated with "Rel" value of "injured" (coeff = −0.53), and with "collapsed houses" (coeff = −0.42)

Multicriteria ranking of districts is performed by VIKOR algorithm, considering districts as "alternatives" and damages as "criteria." With "Rel" data (per 1000 of population)

Table 1
Damages caused by the "921" earthquake

	Dead people (1)	*Injured people (2)*	*Collapsed houses (3)*	*Damaged houses (4)*	*Ratio: (3)/(1)*	*[(3)+(4)]/ [(1)+(2)]*
Nantou County	843	2429	19320	19281	23	12
Taichung County	1119	3606	6532	4062	6	2
Taichung City	113	1112	647	330	6	1

Table 2
The data obtained from Nantou County

		Collapsed Houses		*Damaged Houses*		*Dead People*		*Severe Injured*		*Popul.*
	District	*Abs.*	*Rel.*	*Abs.*	*Rel.*	*Abs.*	*Rel.*	*Abs.*	*Rel.*	*Abs.*
1	Chichi	1816	147.0	834	67.5	42	3.4	18	1.5	12352
2	Jungliau	2542	141.8	1424	79.4	179	10.0	22	1.2	17928
3	Lugu	1140	54.3	1016	48.4	23	1.1	35	1.7	21004
4	Juahan	2731	44.2	2974	48.1	115	1.9	27	0.4	61842
5	Shueili	599	26.0	1231	53.4	8	0.4	9	0.4	23055
6	Mingjian	359	8.4	443	10.4	35	0.8	9	0.2	42673
7	Yuchr	2375	133.8	1476	83.2	14	0.8	10	0.6	17752
8	Guoshing	1913	78.8	1871	77.1	90*	3.7	12	0.5	24277
9	Nantou	5213	49.6	6318	60.1	93	0.9	25	0.2	105150
10	Tasutuen	2557	26.3	4003	41.2	88	0.9	19	0.2	97088
11	Puli	6220	70.2	6610	74.6	210	2.4	57	0.6	88641
12	Shinyi	436	24.6	357	20.1	0	0.0	2	0.1	17722
13	Renai	330	21.6	418	27.4	1	0.1	4	0.3	15278
	Total	28231		28975		898		249		544762

Note: "Abs" denotes the absolute values, and "Rel" denotes the value per 1000 of population (collapsed houses/population/1000).
*There are 22 missing people from Guoshing.

from Table 2, the following ranking is obtained: Jungliau, Chichi, Guoshing, Puli, Yuchr, Lugu, Juahan, Nantou, Tasutuen, Shueili, Renai, Shinyi, Mingjian. With the absolute data the ranking is as follows: Puli, Nantou, Juahan, Jungliau, Tasutuen …

Multicriteria ranking and statistical analysis indicate that the more affected areas include Chichi, Jungliau, Guoshing, Puli, Yuchr. These areas have to be of great concern within the reconstruction planning, although the larger area needs urgent reconstruction, too.

6.2 Multicriteria analysis of reconstruction plans

The alternatives (scenarios) of post-earthquake reconstruction could be generated using the information related to "system parameters" as follows.

s_1, s_2, s_3—as same as for the "921" earthquake epicenter;
s_4—number of reallocated settlements: from 0 up to 5000 houses, in the towns near the faults;
s_5—land use types: existing plan; more forestry, agriculture, and recreation areas; hydropower from small-dam cascades;
s_6—development regulations: zoning, to ban construction within the hazard area, either side near the fault line; different regulations for urban and rural areas;
s_7—fiscal policies: insurance, income tax;
s_8—construction techniques: buildings may be restricted to one or two floors near the fault zone, "smart structures" (Adeli and Saleh, 1999) and "structural optimization" (Koski, 1994) could be considered for this area.

Using different values of the parameters s, five alternative scenarios are generated $(a_1, a_2, \ldots, a_5)$. The alternatives are evaluated according to the established criteria, and the data are presented in Table 3. The use of fuzzy numbers and scores is illustrated by the data for the criterion function f_4. In Table 3 the values of f_3 and f_4 are estimates of potential damages, but actual damages are presented in Tables 1 and 2.

The ranking results obtained by VIKOR with different values of criteria weights are presented in Table 4. The set of compromise solutions consists of $\{a_4, a_3, a_5\}$, with small advantage, and more investigation is needed for the final decision.

Reconstruction scheduling under budgetary constraints could be performed for an accepted solution using multicriteria genetic algorithm (Tzeng and Chen, 1998; Park and Grierson, 1999). Reconstruction within an affected area (13 districts or more) should be considered as activities, one activity for reconstruction within one district. An activity consists of few phases, including repairing, cleaning lots, and building new houses. The criteria for scheduling could be social impact, public preferences, authority preferences, costs, and urgency, that is, "as soon as possible." The yearly budget should be estimated for the time horizon.

6.3 Multicriteria analysis of restoration scenarios

The study by Kozin and Zhou (1988) presents an applied formulation of lifeline systems restoration process in the post-earthquake period by the method of Markov decision process and discrete event simulation. The single criterion method of dynamic programming was applied. By

Table 3
The performance matrix

Criterion	*Unit*	*Ext.*	a_1	a_2	a_3	a_4	a_5
f_1—Reconstruction costs	"921"*C*	*Min*	C	1.5C	1.6C	1.7C	2.0C
f_2—Gross dom. production	*exGDP*	*Max*	GDP	GDP	0.8GDP	0.8GDP	0.7GDP
f_3—Destroyed houses	House	*Min*	10000	5000	3000	2000	500
f_4—Damaged houses	House	*Min*	16666	10000	9455	7148	2583
l ("from")			10000	5000	5000	2000	1000
m ("about")			20000	10000	10000	7000	1000
r ("up to")			20000	15000	12000	10000	5000
f_5—Restoration ability	Week	*Min*	12	8	4	3	2
f_6—Sustainability		*Max*	2	4	6	10	8
f_7—Public acceptability		*Max*	0.2	0.5	0.8	0.4	0.3
f_8—Government preference		*Max*	2	5	8	9	10

computer simulation, the combination of various scenarios and restoration policies were examined to determine the influence of different factors in the restoration of lifeline systems. Initial damage probability states and immediate economic returns of lifeline systems were the two main factors in deciding restoration policy for an assumed probabilistic transition matrix. The optimal restoration policy (for each scenario) was obtained by maximizing the expected economic return from the functioning of the lifeline systems. As a numerical example, the study solved the problem with five scenarios, including eight lifeline systems, with ten capacity states each, and a time horizon of 46 time periods (Kozin and Zhou, 1988). The main characteristics of generated scenarios were as follows:

a_1—The rescue resource in each repair time period varies, and the available amounts were given.
a_2—Scenario is similar to a_1, except the initial probability state vector for some systems changed.
a_3—Parameters in the transition rate formula were changed. This formula represents the geographical and structural characteristics of each system (lifeline).
a_4—The resource supply for reconstruction increased gradually within the time horizon.
a_5—Scenario with same parameters as a_1, but with an exponential transition rate formula.

Using the results from the study by Kozin and Zhou (1988), the data for multicriteria optimization are prepared and they are presented in Table 5. The criteria (for MCDM) are established in this paper, as follows.

f_1—total return within time horizon;
f_2—total return after 23 time periods (of 46 within time horizon);
f_3—number of systems with restored capacity $\geq$ 90% after 23 time periods;
f_4—number of systems with restored capacity $\geq$ 90% after time horizon (46 periods);
f_5—time period when two best restored systems have capacity $\geq$ 90%;
f_6—time period when all lifeline systems have restored capacity $\geq$ 50%.

The ranking lists with different criteria weights are obtained by method VIKOR using data from Table 5. The ranking results are presented in Table 6; the compromise solutions are printed in bold.

The multicriteria ranking results (Table 6) show that the scenarios a_1 and a_2 are top ranked, and the best restoration effects could be achieved under the conditions of these scenarios. According to these results a conclusion could be made as follows: the higher reconstruction priority has to be assigned to the systems (lifelines) with lower initial damage probability state, higher economic return, and better geographical and structural characteristics, trying to provide resources for reconstruction as much as possible in the early time periods.

Table 4
Compromise ranking results

Run	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	$a_j(Q)$ *Ranking*				
1	1	1	1	1	1	1	1	1	a_3(**0.035**)	a_4 (**0.043**)	a_2 (0.298)	a_5 (0.515)	a_1 (1.0)
2	1	1	2	2	2	1	1	1	a_4 (**0.020**)	a_5 (**0.115**)	a_3 (**0.177**)	a_2 (0.403)	a_1 (1.0)

Table 5
The performance matrix for restoration scenarios

	a_1	a_2	a_3	a_4	a_5
f_1—total return within time horizon	15494	15926	14483	14293	10009
f_2—total return after 23 time periods	6781	6599	6343	6071	5655
f_3—restored capacity $\geq$ 90% after 23 time periods	6	1	5	2	1
f_4—restored capacity $\geq$ 90% after time horizon	6	7	6	6	6
f_5—2 best restored systems have capacity $\geq$ 90%	9	27	26	20	28
f_6—all systems have restored capacity $\geq$ 50%	30	43	60*	40	100*

*Extrapolated data.

Table 6
Multicriteria ranking results

	Weights										
Run	w_1	w_2	w_3	w_4	w_5	w_6	*Ranking List* (Q)				
1	1	1	1	1	1	1	a_1 (**0.007**)	a_2 (**0.253**)	a_3 (0.427)	a_4 (0.482)	a_5 (1.0)
2	2	1	1	1	1	1	a_1 (**0.0**)	a_2 (**0.098**)	a_3 (**0.193**)	a_4 (**0.219**)	a_5 (1.0)
3	1	1	1	2	1	1	a_2 (**0.022**)	a_1 (0.477)	a_3 (0.698)	a_4 (0.727)	a_5 (1.0)
4	2	1	2	2	1	2	a_1 (**0.009**)	a_2 (**0.177**)	a_3 (0.373)	a_4 (0.451)	a_5 (1.0)
5	1	1	2	2	2	2	a_1 (**0.005**)	a_2 (0.300)	a_3 (0.457)	a_4 (0.491)	a_5 (1.0)
6	1	1	1	2	1	2	a_2 (**0.034**)	a_1 (0.472)	a_4 (0.695)	a_3 (0.696)	a_5 (1.0)

7 CONCLUSIONS

The multicriteria optimization method may be applied to help decision makers achieve an acceptable compromise. By the compromise ranking method the compromise solution is determined that could be accepted by the decision makers because it provides a maximum “group utility” of the “majority,” and a minimum individual regret of the “opponent.”

The results of multicriteria optimization could indicate the new plan and measures for improving global safety within the area with potential natural hazard. Long-term reconstruction project for earthquake-affected area is needed to provide real data for the developed FUMCO model.

To answer the questions how and when to implement the land use plan over study area, the research should continue by solving the allocation and scheduling problem under budgetary constraints.

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