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Earthquake Disaster Management with Considering the Importance of Recovery

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ABSTRACT: With respect to disasters, earthquake is one of the leading causes of death. Its aftermath can be abated if proper actions take place before the onset of the earthquake. Various sectors in a country are responsible for managing disasters, but the lack of knowledge about the positive effects of their actions makes them reluctant to act decisively. Retrofitting buildings and structures, positioning humanitarian goods, retrofitting transportation links, and devising a disaster response plan all make a city more resistant. The main aim of this paper is to present a robust model to investigate the effect of considering recovery costs on decision making. In this model, the importance of each region changed with due attention to imposed costs to the region without any action. The result shows a 13 percent improvement compare to the previous model. Also, this paper highlights the significance of pre-disaster action on the recovery costs and the importance of taking action before it is too late.

Keywords: Disaster Engineering, Mathematical Modelling, Sustainability, Transport Management, Transport Planning.

INTRODUCTION

Studies on previous earthquakes show that disasters threaten regions with buildings that lack adequate structural resistance, particularly when there is a late emergency response. The situation is aggravated when various important roads are blocked and humanitarian supplies (e.g., water, food, medical goods, and survival equipment) cannot get through on time (Chen and Li, 2017; Chen and Yu, 2016; Das, 2018; Goldschmidt and Kumar, 2016; Iqbal et al., 2018; Mulay et al., 2016; Nadi and Edrisi, 2017; Vitoriano et al., 2011; Zhu et al., 2014).

Not only transportation plays a key role in facilitating disaster relief, its significance in recovery and economic disruption is revealed in many case studies, such as the Hyogoken-Nanbu (Kobe) earthquake. The highway recovery time after this earthquake was recorded as 21 months in comparison with other lifeline recovery times that were all below 4 months (Chang and Nojima, 2001).

To save lives after a catastrophic event, it is essential that both preventive and recovery actions take place. Disaster management, composed of 1) mitigation, 2) preparedness, 3) response, and 4) recovery phases, is a systematic process that aims to reduce the

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negative impacts or consequences of adverse events. Mitigation is the set of measures taken to reduce the impact of disasters or eliminate them. Preparedness helps to avoid the consequences of a disaster, by preparing the community for hazards. Response means acting according to emergency plans to preserve life, property, the environment, and the community's social, economic and political structure. Recovery involves long-term actions that will restore normalcy to the affected areas (Cheraghi and Hosseini, 2017; Edrissi et al., 2015; Yan et al., 2017; Mowll and Brunsdon, 2014).

Altay and Green (2006), who examined the role of Operations Research and Management Science (OR/MS) in Disaster Operations Management (DOM), 44%, 21.1%, and 23.9% of reviewed papers addressed mitigation, preparedness, and response phases, respectively. Therefore, the recovery phase, which makes up only 11% of the reviewed articles, is in dire need of more research. Galindo and Batta (2013) also investigated this statistic and stated that the recovery phase still needs more study.

Some may argue that the recovery phase may not be as important as other phases, but according to Altay and Green (2006) and Galindo and Batta (2013) studies, disaster management decisions may be improved by considering this phase. Also, in a lot of studies neglected the imposed costs to the societies and used some other criteria.

This paper focuses on determining the role of considering recovery costs on decision making. To do so, at first, imposed costs without pre-disaster actions enumerated and region importance changed by integration of these costs. The results show a 13 percent improvement in recovery costs compare to the proposed model by Edrissi et al. (2013). In other words, this study tried to demonstrate the importance of the neglected phase by Edrissi et al. (2013). The main contribution of this paper is to integrate all four phases of disaster management in decision making and based on this, it can help policymakers on choosing the best possible set of decision for a city.

The remaining part of this paper is organised as follows. A literature review is provided in the next section. Problem description and methodology section comprises problem components and definitions. Also, Edrissi et al. (2013) method is briefly described; appropriate recovery indexes are investigated for a simple network; and recovery costs are defined, classified, and evaluated. Numerical example of the extended model and conclusions are the other parts of this paper.

LITERATURE REVIEW

Recovery Phase

Recovery includes post-disaster activities from few hours to years that aim to return the system to the normal state. As noted in literature (Altay and Green, 2006; Galindo and Batta, 2013), the least attention has been paid to the recovery phase compared with other disaster management phases, and the results of this inattention are observable in reality. For instance, after more than a decade of the Bam earthquake in 2003, the unrecovered ruins are still observable (USGS, 2006). In order to be more familiar with studies conducted in this field, some of the most relevant studies to the current research are analysed and presented as follows:

One of the first studies in this area was conducted by Cret et al. (1993), who addressed the impact of earthquake on decision making related to gas network shut-off using Fuzzy set theory with the aim of recovery. In another research, Song et al. (1996) conducted a comprehensive study on earthquake damages using Fuzzy theory. Leelawat et al. (2015) also studied the cooperation management process among organizations in the recovery and reconstruction of the post-earthquake and post-tsunami damages that happened in Japan in 2011. They emphasized the need to create a system based on mutual trust, cooperation, and respect among responsible organizations.

Kamamura et al. (2015) investigated the multiple stage recovery of the transportation network and proposed a multi-objective optimization problem that consists of the following: 1) maximizing traffic ratio after the recovery, and 2) minimizing the proportion of changed routes at each step. They formulated their problem in the form of linear programming and also proposed a heuristic algorithm for that. Karlaftis et al. (2007) also proposed a budget allocation methodology for rehabilitation of city infrastructures following a natural disaster. They used a genetic algorithm with 3 stages and tested it for Athens, Greece.

Khademi et al. (2015) investigated the post-disaster vulnerability of Tehran transportation network. They also proposed a method to evaluate response and recovery routes following an earthquake in this city. The most important results of the study were the determination of relief trips vulnerability and zone exposure index. Koike and Miyamoto (2017) proposed a model to evaluate short-term economic losses caused by earthquake. The model consists of two sub-models; one of them calculates the travelling time of damaged network, and the other determines economic damages.

Many other studies have addressed recovery from the theoretical and practical viewpoints of project management, with the aim of organizing departments and achieving better performance of disaster management projects (El-Anwar et al., 2010; Kalkman and Waard, 2017; MacAskill and Guthrie, 2016).

Multi-Agent Multi-Phase Nature of Disaster Management

Despite the importance of considering disaster management as a unit problem, only a few studies addressed this aspect. Among the few studies that addressed this aspect, some only studied a limited area of disaster management, such as emergency response, which includes locating the warehouses (or shelters) and distribution of relief before and after a disaster (Mete and Zabinski, 2010), while others just presented a qualitative description of cooperation between agencies and integration of disaster management phases (McLoughlin, 1985; Tufekci and Wallace, 1998; Balcik et al., 2008; Schulz and Blecken, 2010; Gonzalez, 2010). Furthermore, some of the most related and recent studies are analysed below:

Rodriguez-Espindola et al. (2015) proposed a multi-agent method for disaster preparedness by incorporating Geographical Information System (GIS) in the multi-objective model. The aim of this approach was to determine the locations of emergency response facilities and inventories and to distribute them during flood disasters. In another study, Wang et al. (2016) proposed a bi-objective model for allocating shelter and emergency response routing problem considering the reliability of transportation network. Their approach used Genetic Algorithm (GA) to maximize the reliability of routes between residential areas and shelters. Also, Manopiniwes and Irohara (2017) proposed a stochastic Mixed Integer Linear Programming (MILP) model for integrated decision making regarding shelter locations, evacuation, and vehicle routing in pre- and post-disaster phases. The shelter cost and shelter fairness criteria were used in the model.

Clearly, no research has studied the reciprocal impacts of the four phases of disaster management and their integration. Following Altay and Green (2006) as well as Galindo and Batta's (2013) research directions, Edrissi et al. (2013) proposed a coordinated multi-agent multi-phase model, which integrates the mitigation, preparedness, and response phases but disregards the recovery phase. Based on these, the main contribution of this paper is highlighted as the extension of Edrissi et al. (2013) findings to integrate the recovery phase in the model, in order to build more robust decision support systems.

PROBLEM DESCRIPTION AND METHODOLOGY

Problem Components

The collapse of buildings is the most important reason for the high number of deaths in an earthquake. The death toll is based on the population of every zone and the percentage of seismically weak buildings. To provide efficient emergency relief to victims, it is essential to prepare humanitarian goods at predetermined locations beforehand. An effective emergency response system is one that immediately distributes emergency response supplies to the affected areas. The time it takes for the supplies to reach their destination (called the emergency delay) affects the survival probability, which decreases with time and has a negative exponential decay function. Therefore, the transportation network plays a key role in determining the emergency delay. The failure of any link of the transportation infrastructure may increase the emergency delay and intensify the disaster.

To resolve the mentioned issues, a lot of organizations may be determined. Based on this, Edrissi et al. (2013) determined three main sectors responsible for these issues that are as follows:

The Building Renovation Sector (BRS), a responsibility of the private sector, decides what portion of which regions require building rehabilitation; this sector is involved in the mitigation phase. The Transportation Sector (TS), under the supervision of the municipality, decides which links need retrofitting to better dispatch humanitarian aid to people at fixed distribution points at a time of disaster; this sector is also involved in the mitigation phase. The Emergency Response Sector (ERS), under the management of the government, devises disaster counteraction plans for both the preparedness and the response phases, focusing on storage and distribution of supplies.

The objective of Edrissi et al. (2013) study was to investigate which areas need building improvement and restructuring and to what extent, where the humanitarian goods need to be located and in what proportion, and which transportation network links are more important in the mobility of the goods as well as those that are weak and in need of improvement. Edrissi et al. (2013) study comprised of a Master Problem (MP) that is looking for minimizing the expected death toll considering a predetermined budget value and other sub-problems (SP). The decisions of the primary sectors are outlined by solving three different sub-problems: The Building Renovation Problem (BRP), the Emergency Location/Allocation Problem (ELAP), and the Network Improvement Problem (NIP). More detailed information presented in the appendix. Also, the flowchart of Edrissi et al. (2013) problem is shown in Figure 1.

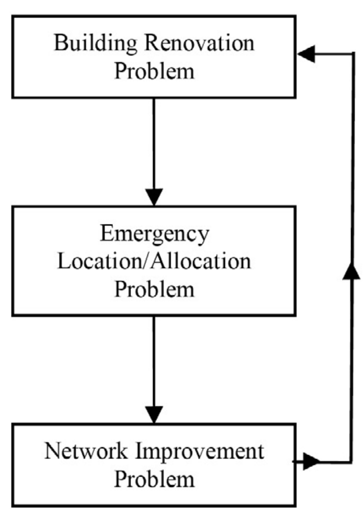


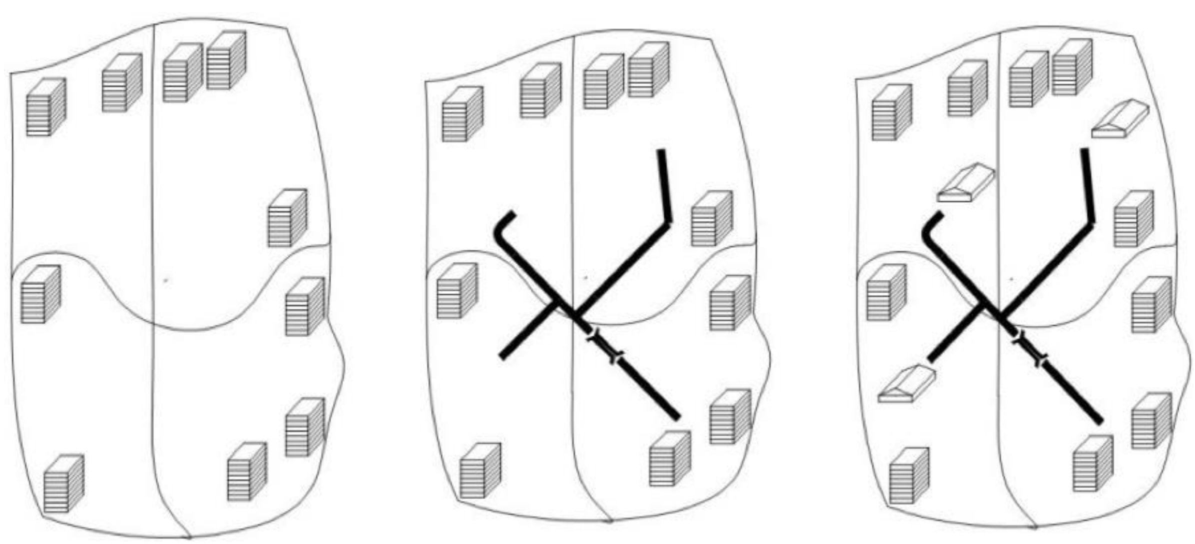
Fig. 1. Flowchart of coordination in disaster management (Edrissi et al., 2013)

The budgets of BRS, ERS, and TS sectors will be denoted by B_z, B_x, and B_y respectively, which are usually independent of each other in reality. In the proposed model, the budgets are predetermined and have specific values. There are two strategies to save lives in an earthquake; retrofit buildings so they do not collapse and rescue people by emergency response.

Definition of Parameters

The hypothetical city is divided into several regions, and each region is divided into zones; *sl* is a zone in region *s*. The population of zone *sl* in the city is represented by P_{sl}, and q_{sl} (building vulnerability ratio) denotes the percentage of the buildings of zone *sl* that will collapse at the time of a design earthquake occurrence (Figure 2a). The building vulnerability ratio is dependent on the magnitude of the design earthquake; a higher magnitude of design earthquake leads to a bigger building vulnerability ratio (Coburn et al., 1992). A continuous decision variable called z_{sl} (z_{sl} = 0 no action, z_{sl} = 1 full retrofitting) indicates the ratio of zone *sl* that has been decided to be stabilized. The zones of the city are connected to one another by transportation links. Let *N(V, A)* be a network of concern with *V* as the set of nodes and *A* as the set of links (Figure 2b). Every zone has an initial inventory of humanitarian goods, which has to be dispatched at the time of disaster; that of zone *k* is denoted by (W_k) (Figure 2c).

It is clear that the emergency delay time plays a key role in the efficacy of the response. As the delay time increases, more lives would be lost. Therefore, the dispatched emergency supplies ($x^{k,sl}$) must be multiplied by a survival function ($S(\tau^{k,sl})$), which depends on the emergency delay time ($\tau^{k,sl}$) from zone *k* to zone *sl*. The survival function, derived from Coburn et al. (1991), is an expression of the effectiveness of the emergency response. If $\tau^{k,sl}$ is the time it takes to travel from zone *k* to zone *sl* from the time of the occurrence of the earthquake, then $S(\tau^{k,sl})$, a value between one and zero, will present the efficacy of the relief operations. In other words, at the onset of a disaster, a ratio of (1-*a*) of the population would die (Figure 3). The ratio of the rescued population will monotonically decrease as a function of time, and approach zero. This function is mathematically set to be a function, as shown in Figure 3. Similar versions of the survival function are also used in Fiedrich et al. (2000).



(a) (b) (c)

Fig. 2. a) Zones in a city, b) Transportation network, and c) Emergency supplies

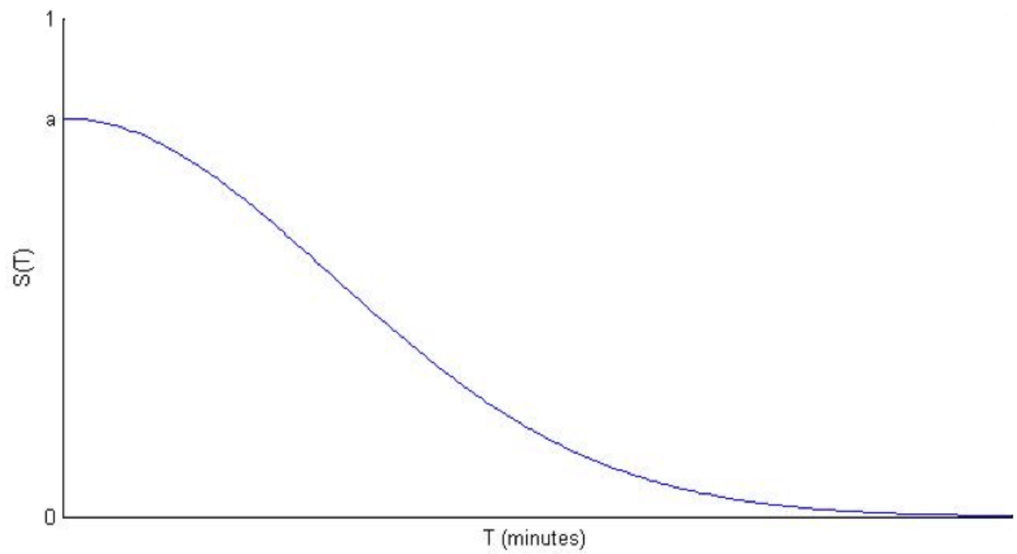


Fig. 3. Survival function $S(\tau) = ae^{b\tau^c}$, $(a > 0, c > 0, b < 0)$ as a function of travel time (in minutes)

Recovery Index

Disaster management is composed of four phases: mitigation, preparedness, response, and recovery. Recovery involves long-term actions after the immediate impact of the disaster to stabilize the community and to restore some semblance of normalcy. As mentioned before, the area in dire need of more research, especially in OR/MS, is disaster recovery. In order to effectively investigate the performance of the disaster management procedures, a small problem, illustrated in Figure 4 and Tables 1-3, are designed, and indices that indicate the state of recovery of the city are investigated. Tables 1-3 represent the link data, region data, and the scenario data respectively. The survival function for this example is defined as $S(\tau) = 0.8(e^{-0.0001\tau^2})$.

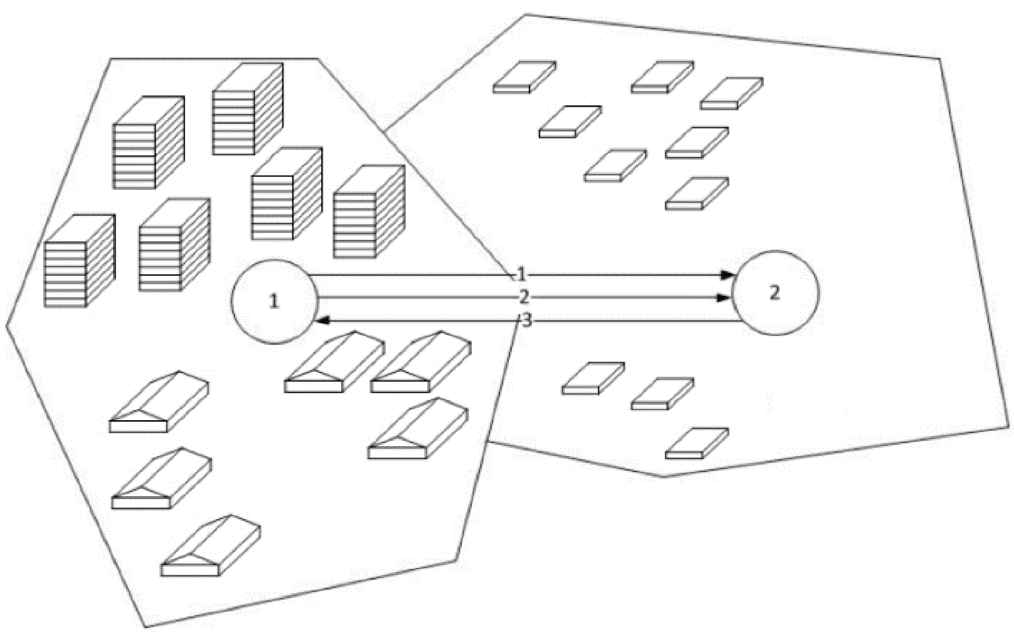


Fig. 4. Test problem 1

Table 1. Link data for the hypothetical city of Figure 4

Link	Failure probability (Q_{ij})	Cost of entire retrofitting (monetary units)	Time-volume function (minutes)
1	0.1	100	$T_1 = 40 + 0.002X_1$
2	0.2	170	$T_2 = 30 + 0.01X_2$
3	0.15	130	$T_3 = 30 + 0.005X_3$

Table 2. Zone data for the hypothetical city of Figure 4

Region	Unstable building ratio (q_{sl})	Cost of entire retrofitting (monetary units)	Population (P_{sl})	Cost of storing emergency supplies to save one human's life (monetary units)	Present available emergency supplies
1	0.1	700	15000	0.2	200
2	0.3	1200	10000	0.5	400

Table 3. Description of every scenario with its associated probability and travel time (in minutes) from the zone (1) to zone (2) and vice versa

Scenario (c)	Failed link	Probability	$\tau^{1,2}$ (min)	$\tau^{2,1}$ (min)
1	-	0.612	48.28	45
2	1	0.068	90	45
3	2	0.153	52	45
4	3	0.108	48.28	∞
5	1,2	0.017	∞	45
6	1,3	0.012	90	∞
7	2,3	0.027	52	∞
8	1,2,3	0.003	∞	∞

In Table 1, time-volume function shows the travel time of a link based on how many cars go through it. In Table 2, unstable building ratio shows what proportion of buildings in a region will collapse if an earthquake with predetermined magnitude occurs. Also, the cost of entire retrofitting shows the budget that is required to change the unstable building ratio of that region to zero. After the disaster, each link may or may not fail (2 states) and because the network has 3 links, the post-disaster network may have any of 2^3 situations, which is called scenario and is illustrated in Table 3.

City Disaster Exposure Index (CDEI), Life Assurance Index (LAI), and Security Index (SI) are recovery indexes. The CDEI represent the at-risk population ratio of a city. The LAI is defined as the ratio of all the rescued individuals to the total at-risk population of a city. Since the number of rescued people never exceeds the total at-risk population of a city, this index is between zero (loss of the whole population) and one (the entire population is rescued). Security Index (SI) is the ratio of people who were saved by the BRS, and therefore have shelter, to the number of rescued people by both the ERS and the BRS (overall saved people). Since the number of saved people with homes doesn't exceed the total rescued population, this index is between zero (everyone is saved by ERS) and one (everyone is saved by BRS).

$$\text{CDEI}=\frac{\text{initial at risk population of the city}}{\text{initial population of the city}}=\frac{\sum_{sl}\{P_{sl}.q_{sl}\}}{\sum_{sl}\{P_{sl}\}} \tag{1}$$

$$\text{LAI}=\frac{\text{total number of rescued people}}{\text{initial at risk population of the city}}=\frac{\sum_{sl}\{P_{sl}.q_{sl}.(\bar{z}_{sl})+\sum_k x^{k,sl}{}_c.S(\tau^{k,sl}{}_c)\}}{\sum_{sl}\{P_{sl}.q_{sl}\}} \tag{2}$$

$$\text{SI}=\frac{\text{total number of rescued people who have homes}}{\text{total number of rescued people}}=\frac{\sum_{sl}\{P_{sl}.q_{sl}.(\bar{z}_{sl})\}}{\sum_{sl}\{P_{sl}.q_{sl}.(\bar{z}_{sl})+\sum_k x^{k,sl}{}_c.S(\tau^{k,sl})\}} \tag{3}$$

Figures 5-7 represent the LAI, SI, and both of them together, when the sum of the three sector budgets are set to be a constant value (Bx+By+Bz = 1350). Figure 5 illustrates how the LAI increases when a substantial budget is invested in the ERS, whereas if this budget was invested in the BRS, a loss of LAI would occur. This notion is explained by the fact that the cost of saving lives by the BRS is higher than that of the ERS; therefore, with a limited budget, it is more effective to save lives through the ERS. The blue area in the figure displays a larger budget in the TS, which is unreasonable because an efficient transportation network without adequate emergency response supplies is worthless.

Figure 6 illustrates how the SI is varied against changes in the ERS and BRS budgets. When a larger budget is allocated to BRS, more people get the chance to survive the disaster in their intact homes. Therefore, the economic condition would be less harmed. On the other hand, if a larger portion of the entire budget is assigned to the ERS, people survive the disaster by being pulled out from their collapsed homes and the economy is damaged.

The LAI possesses a greater importance compared with the SI. A low LAI is never recoverable, because it is an indication of how many people survived the disaster. The SI, on the other hand, is recoverable because buildings could be rebuilt and the economy could, therefore, recover. By comparison between the SI and LAI, in Figure 7, it is observed that the LAI is acceptable for a range of budgets (red region), and the SI is varied in this region. This is explained by the BRS budget (By).

The BRS plays a key role in evaluating the two recovery indexes. As the BRS budget (By) increases, a lower budget is assigned to the ERS. This change decreases the LAI, because it is more affordable to save lives through an emergency response plan. However, a high BRS budget means that more buildings would be standing after the disaster and the economic condition would be better. A central decision maker can observe what ratio of budgets with a high LAI also obtains a high SI.

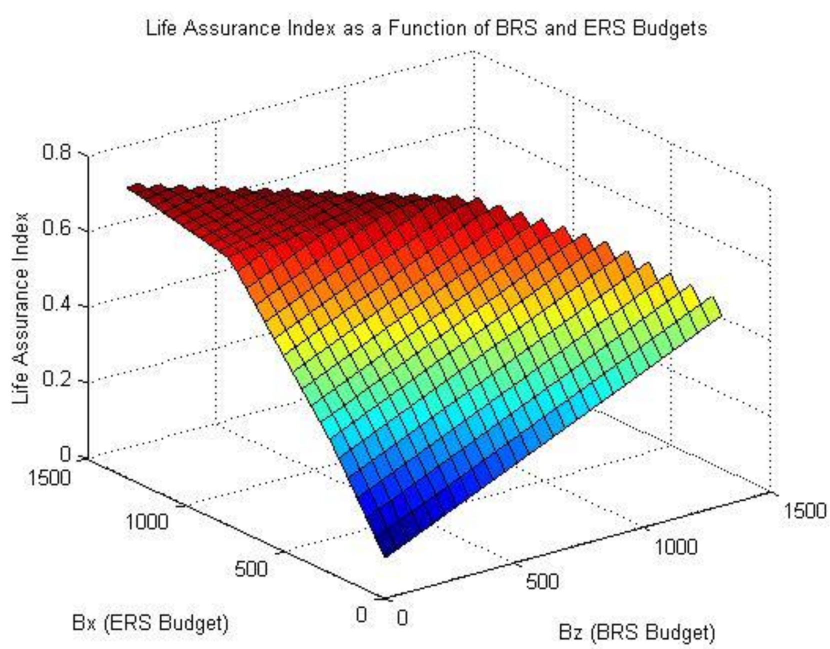


Fig. 5. LAI as a function of the BRS and ERS budgets when the sum of the BRS, ERS, and TS budgets is constant and equal to 1350

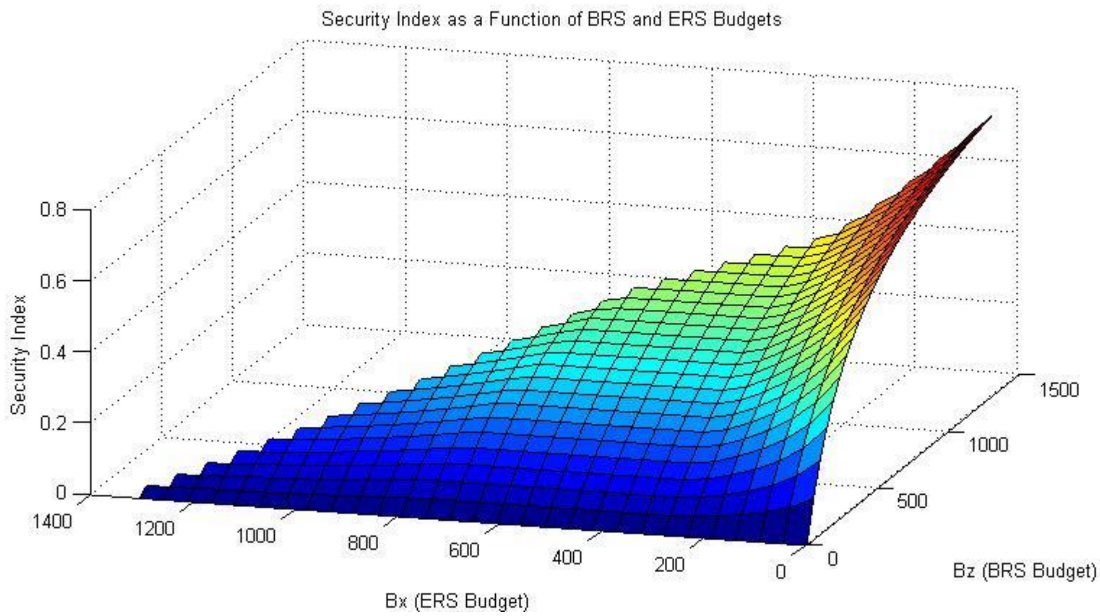


Fig. 6. SI as a function of the BRS and ERS Budgets when the sum of the BRS, ERS, and TS budgets is constant and equal to 1350

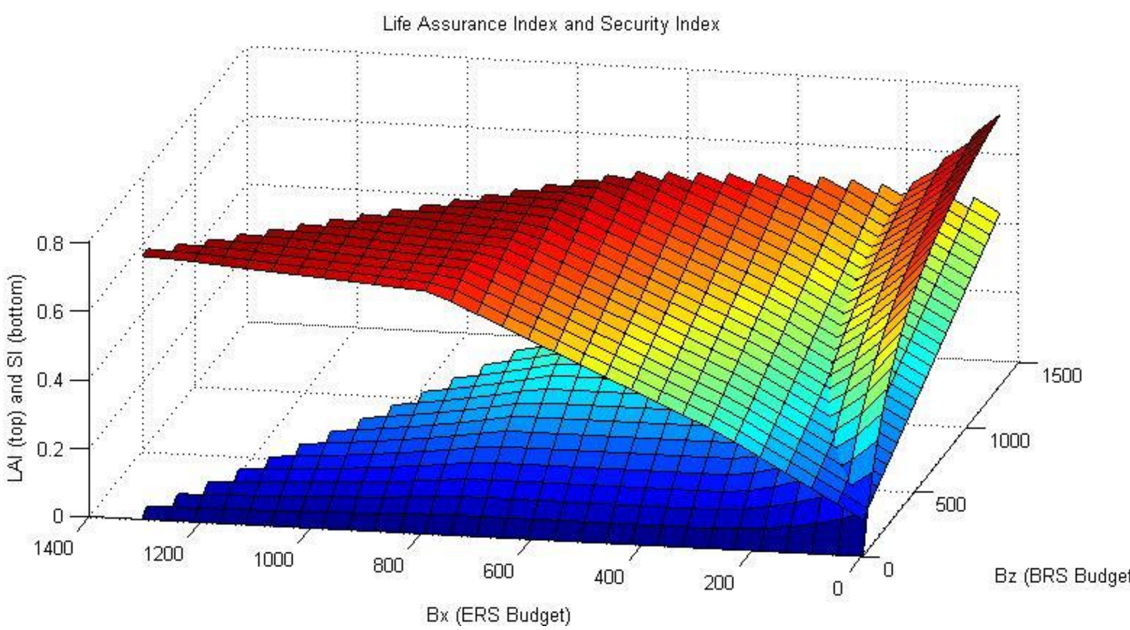


Fig. 7. Comparison between the LAI and the SI when the sum of the BRS, ERS, and TS budgets is constant and equal to 1350

Recovery Costs

Earthquakes cause major damages to the assets of a community, leading to disruption. While much attention has been paid to lost lives and fixed assets (Boswell et al., 1999), other assets of a community have been less studied. With respect to coastal disasters, Gaddis et al. (2007) introduced major costs to human, social, built, and natural capital, and examined the spatial and temporal costs in different cost accounting approaches. In this section, we considered five major costs (natural, social, human, passing, and built costs) in the response and recovery phases (post-disaster) and investigated the effects of pre-disaster efforts on post-disaster costs.

Natural Cost

Natural cost is the penalty of losing natural resources that yield a flow of valuable ecosystem goods. For simplicity, we only considered the influence of debris on the environment and neglected other costs related to natural, renewable, and non-renewable sources. In fact, these are the costs that one may influence (decrease). Others are not in the hands of human beings, at least not yet.

Debris removal

Hiring personnel to load debris disposal trucks is costly. The cost of debris removal is computed by defining k_1 and k_2, which denote the required area per person (for the living) and the ratio of debris generation (in tons) per square meter respectively. So, the debris removal cost is calculated as follows:

$$C_{11} = c_{11}\times k_1\times k_2\times\sum_{sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})\} \quad (4)$$

where c_{11}: represents the cost of removing one ton of debris, and $\sum$: represents the population whose homes are damaged by the earthquake.

Debris transporting

After removing debris and loading them on the dump truck, they are transferred to the landfills for disposal. Therefore, the debris transportation cost is associated with the amount of debris and the distance between the affected regions and the landfill. Hence, the debris transportation cost is calculated as follows:

$$C_{12} = c_{12}\times k_1\times k_2\times\sum_{sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})\}\times d_{sl} \quad (5)$$

where c_{12}: denotes the cost of transporting one ton of debris for one kilometre, and d_{sl} : is the distance between region *sl* and the dump site in kilometres.

Landfill cost

The minimum cost that is associated with dumping debris on a landfill is the price of the landfill area. Consequently, the landfill cost is calculated as follows:

$$C_{13} = c_{13}\times \text{Ar}\times\frac{k_1 * k_2}{\text{cap}}\times\sum_{sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})\} \quad (6)$$

where cap stands for the capacity of the dump truck, and *Ar*: is the area that is consumed by debris. C_{13} and c_{13}: are the total and average unit land price of the dump area, respectively.

Social Cost

The social cost is the loss of the connections within and between social networks. These networks can vary from people within a family to a virtual community. Also, any factor that can cause a mental, psychological, or social inconvenience is placed under social costs.

Loss of family members

To figure out the cost of psychological cure after losing a family member, it is assumed that the role (relation, e.g. father) of a missing person in the family doesn't have any effect on this cost. This means that the family members of any person that died in the disaster need c_{21} money on average for psychological cure. Thus, this cost is computed as follows:

$$C_{21}= c_{21}\times\sum_{sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})-\sum_k x^{k,sl}.S(\tau^{k,sl})\} \quad (7)$$

where C_{21}: denote the total cost of psychological.

Asset loss

The costs of losing one's property (home, appliance, utilities, and belongings) are considered as an asset loss:

$$C_{22} =\sum_{sl} c_{22,sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})\} \quad (8)$$

where C_{22} and $c_{22,sl}$: represents the total and average unit asset belonging to any person (the latter in zone *l* of region *s*), respectively.

Market loss

We assume that the distribution and the structural stability of non-residential and residential buildings are the same. If r represents the ratio of commercial building units destroyed per person that died in the earthquake and c_{23} denotes the worth of a non-residential building and its contents, we arrive at the following:

$$C_{23} = c_{23}\times r\times\sum_{sl}\{P_{sl}.\, q_{sl}.\, (1-\bar{z}_{sl})\} \tag{9}$$

where c_{23} and C_{23}: are the average unit and total of this cost, respectively.

Career loss

If a person is alive after the earthquake but his work position is destroyed, the government is responsible for compensating for the job loss. This cost is based on the people who are alive after the earthquake. R^{sl} represents the proportion of employment per person, and c_{24} shows the cost of recreating that job. In other words, the government should make job opportunities for anybody that is alive after the disaster whose job was destroyed, we arrive at the following:

$$C_{24} = c_{24}\times\sum_{sl} q_{sl}.\, R^{sl}\{P_{sl}.\, (1-q_{sl}) + P_{sl}.\, q_{sl}.\, z_{sl} + \sum_{k} x^{k,sl}.\, S(\tau^{k,sl})\} \tag{10}$$

where C_{24}: is the total of this cost.

Human Cost

The human cost is quantified in terms of human lives, burial of human remains, medical care, and emergency rescue operations.

Burial cost

After the earthquake, the departed should be buried. Hence, this cost is related to the CTDL.

$$C_{31} = c_{31}\times\sum_{sl}\{P_{sl}.\, q_{sl}.\, (1-\bar{z}_{sl}) - \sum_{k} x^{k,sl}.\, S(\tau^{k,sl})\} \tag{11}$$

where c_{31} and C_{31}: represent the average unit and total cost of burial services, respectively.

Rescue cost

After the earthquake, the emergency response sector begins to search for people who are alive and stuck under the disaster debris. Also, people who survived the earthquake spontaneously try to search for other people without any technical instruments. Although the latter method of search and rescue is not well organized and cannot save many lives, it is costly.

$$C_{32}=c_{32}\sum_{sl}\{P_{sl}.\, q_{sl}.\, (1-\bar{z}_{sl})\} + c'_{32}\times\sum_{sl}\{\sum_{k} x^{k,sl}.\, S(\tau^{k,sl})\} + c''_{32}\times\sum_{sl}\{\sum_{k} x^{k,sl}.\, S(\tau^{k,sl}).\, D^{k,sl}\} \tag{12}$$

where c_{32}, c'_{32} and c''_{32}: denote the cost of rescue made by civilians, by the emergency response sector and the cost of transferring wounded individuals to hospitals (per person per kilometre). $D^{k,sl}$: is the distance between zone *k* and zone *sl*.

Medical care cost

People who were saved by emergency response are moved to hospitals for further medical care. If c_{33} represents the cost of medical care per person, we arrive at the following:

$$C_{33} = c_{33}\times \sum_{sl}\{\sum_{k} x^{k,sl}.\, S(\tau^{k,sl})\} \tag{13}$$

where c_{33} and C_{33}: are the average unit and total of this cost, respectively.

Death toll

The penalty of losing one life (life insurance) is proportional to the death toll.

$$C_{34} = c_{34}\times\sum_{sl}\{P_{sl}.\, q_{sl}.\, (1-\bar{z}_{sl}) - \sum_{k} x^{k,sl}.\, S(\tau^{k,sl})\} \tag{14}$$

where c_{34} and C_{34}: are the average unit and total of this cost, respectively.

Transitional Cost

The transitional costs are those that are temporary and will be diminished after a period of time.

Authorities' involvement cost

The authorities, having the legal power to make and enforce the law, are involved in making decisions for helping people in the disaster zone to return to normalcy:

$$C_{41}=c_{41}\times t\times\sum_{sl}\{P_{sl}.q_{sl}.(1-\bar{z}_{sl})\}+c'_{41}\times t'\times\sum_{sl}\{\sum_k x^{k,sl}.S(\tau^{k,sl})\}+c''_{41}\times t''\times\sum_{sl}\{\sum_k x^{k,sl}.S(\tau^{k,sl})\} \quad (15)$$

where t: is average occupancy hours per authority figure for every victim of the disaster; t': is the average occupancy hours per authority figure per rescued person, and t'': is the average occupancy hours per authority figure per person in need of housing. c_{41}, c'_{41}, and c''_{41}: represent the respective average unit costs of time per hour.

Temporary housing cost

The cost of temporary housing for homeless families due to an earthquake is calculated based on the number of displaced people and the time needed to move them to permanent houses. If ζ represents the average time that is needed to move all the displaced people from temporary housing to permanent ones, then we arrive at the following:

$$C_{42}=c_{42}\times\sum_{sl}\{\sum_k x^{k,sl}.S(\tau^{k,sl})\}\times\zeta \quad (16)$$

where c_{42}: denotes the average cost of service for one person in temporary housing for one day, and C_{42} is the total of such cost.

Built Cost

These costs estimate the fixed asset losses that occur in a disaster; they include losses to public, commercial, industrial, agricultural and residential infrastructure. Determining the monetary value of these losses is often complicated by the market value of properties not restored.

Permanent housing cost

This cost concerns housing construction for homeless families due to earthquake. This cost is related to the parameters that are considered in temporary housing cost, so we can write as follows:

$$C_{51}=\frac{c_{51}}{s}\sum_{sl}\{\sum_k x^{k,sl}.S(\tau^{k,sl})\} \quad (17)$$

where c_{51}: is the cost of providing housing for one person, and C_{51}: is the total of such costs.

Transportation network renovation cost

Assuming that construction cost is the same as before the earthquake, we can state that the transportation network damage cost is equal to its renovation cost before the earthquake.

$$C_{51}=\sum_{(i,j)\epsilon A}(1-y_{ij}).q_{ij}.c_{ij} \quad (18)$$

Repair cost of standing homes

Standing houses after an earthquake are partially damaged, so they should be repaired to provide a secure place for their inhabitants.

$$C_{53}=c_{53,sl}\times k_1\times\sum_{sl}P_{sl}.\{1-q_{sl}.(1-\bar{z}_{sl})\} \quad (19)$$

in which k_1: is defined as required area per person, and $c_{53,sl}$: is the average unit renovation cost in zone sl. $c_{53,sl}$: is the average cost of repairing a house in region s and zone l.

Table 4 illustrates the mentioned costs, which are related to the number of people under collapsed buildings and the number of rescued people. For simplicity, we neglected the transportation network renovation cost, career loss cost, and the repair cost of standing buildings. At last, we can compute the final cost (lower bound) due to an earthquake occurrence as follows:

$$FC=\{\sum_{sl}\{P_{sl}.\,q_{sl}.\,(1-\bar{z}_{sl})\}\,.\,\alpha\}+\{\sum_{sl}\{\sum_{k}x^{k,sl}.\,S(\tau^{k,sl})\}\,.\,\beta\} \quad (20)$$

where

$$\alpha=(c_{11}*k_1+c_{12}*k_1+c_{12}*w*d*k_1/cap\;+\;c_{21}+c_{22}+\;c_{23}+c_{31}+c_{32}*k_2+c_{34}+c_{41}*t)$$

$$\beta=(-c_{21}-c_{32}+c'_{32}+c''_{32}+c_{33}-c_{34}+c'_{41}*t'+"c''_{41}*t''+c_{42}*\zeta+c_{51}/s)$$

A NUMERICAL EXAMPLE OF THE EXTENDED MODEL

To implement the mentioned costs in the model, the importance of every region in the BRP in Edrissi et al. (2013) study was altered (i.e. Eq. (21) is changed to Eq. (22)). Parameter α, which is the cost associated with trapped individuals under the debris, and parameter β, which is the cost of rescued people, are applied as shown in Eq. (22). It is clear that β is usually negative because saving individuals is more beneficial rather than costly.

$$I_{sl}=P_{sl}q_{sl}-\sum_{k}x^{k,sl}\,.\,S(\tau^{k,sl}) \quad (21)$$

$$I_{sl}=\alpha P_{sl}q_{sl}+\beta\sum_{k}x^{k,sl}.\,S(\tau^{k,sl}) \quad (22)$$

To illustrate the effects of the modified version, a more complex example is given below (see Figure 8), and the results are compared with the original model (Edrissi et al., 2013).

Table 4. Summary of the costs of recovery presented in the problem description and methodology section

Cost group	Cost	$\sum_{sl}\{P_{sl}.\,q_{sl}.\,(1-\bar{z}_{sl})\}$	$\sum_{sl}\{\sum_{k}x^{k,sl}.\,S(\tau^{k,sl})\}$
Natural cost	Debris removal	$c_{11}*k_1$	-
	Debris transporting	$c_{12}*k_1$	-
	Landfill cost	$c_{13}*w*d*k_1/cap$	-
Social cost	Loss of family members	c_{21}	$-c_{21}$
	Asset loss	c_{22}	-
	Market loss	$c_{23}*r$	-
	Career loss	-	$c_{24}*q*R$
Human cost	Burial cost	c_{31}	$-c_{31}$
	Rescue cost	$c_{32}*k_2$	$c'_{21}+c''_{21}$
	Medical care cost	-	c_{33}
	Death toll	$"c_{34}"$	$"-C_{34}"$
Passing Cost	Authorities involvement cost	$"c_{41}"*t$	$"c'_{41}"*t'+"c''_{41}"*t''$
	Temporary housing cost	-	$c_{42}*\zeta$
Built cost	Permanent housing cost	-	c_{51}/s
	Transportation network renovation cost	-	-
	Repair cost of standing homes	-	-

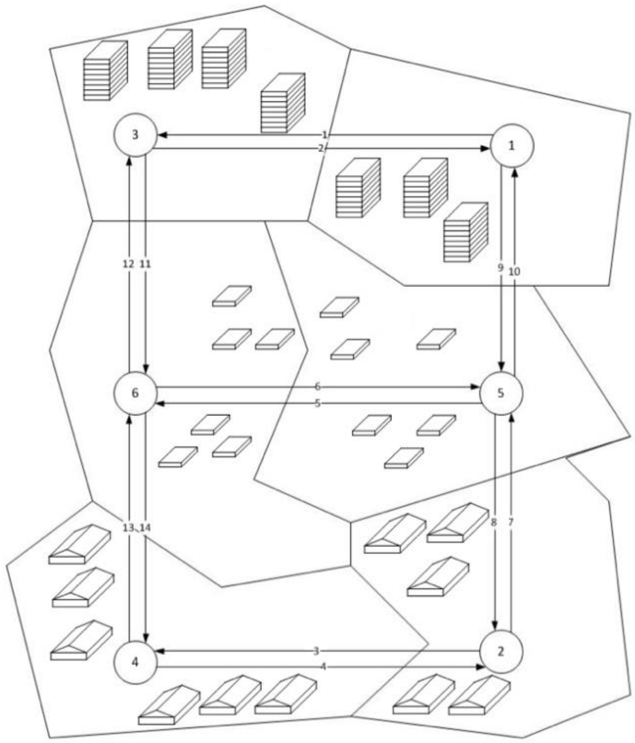


Fig. 8. The hypothetical city with 6 regions and 14 transportation networks links

Table 5. Link characteristics with their corresponding full retrofitting cost (travel time-volume function is $T_{ij} = a_{ij}+b_{ij}.x_{ij}$, where x_{ij}: is the traffic volume in link *(i, j)*)

Link number	***i***	***j***	a_{ij}	b_{ij}	Q_{ij}	$C_{ij}(10^9)$
1	1	3	20	0.01	0.15	30
2	3	1	20	0.01	0.15	30
3	2	4	25	0.01	0.15	30
4	4	2	25	0.01	0.15	30
5	5	6	20	0.1	0.3	30
6	6	5	20	0.1	0.3	30
7	2	5	30	0.05	0.05	12
8	5	2	30	0.05	0.05	12
9	1	5	30	0.08	0.05	12
10	5	1	30	0.08	0.05	12
11	3	6	35	0.05	0.05	12
12	6	3	35	0.05	0.05	12
13	4	6	30	0.05	0.05	12
14	6	4	30	0.05	0.05	12

Table 6. Region and emergency supply characteristics

Region	**Population (1000)**	**Unstable building ratio**	**Cost of entire retrofitting (monetary units) (10^8)**	**Present available emergency supplies**	**Cost of settling emergency supplies to save one human's life (monetary units) (10^7)**
1	60	0.05	40	200	1
2	110	0.08	88	0	10
3	80	0.07	50	500	5
4	90	0.08	84	0	10
5	80	0.09	160	1000	5
6	120	0.08	152	500	5

Table 7. Origin/destination demand at the onset of the earthquake

Origin \ Destination	1	2	3	4
1	0	2000	2000	1000
2	200	0	1000	2000
3	200	100	0	1000
4	100	200	100	0

Table 8. Recovery unit costs

Recovery unit costs							
c_{11}	c_{12}	c_{13}	c_{21}	c_{22}	c_{23}	c_{31}	c_{32}
2.0E+04	2.0E+04	2.0E+05	1.0E+06	2.0E+07	3.0E+09	1.0E+07	6.0E+04
c'_{32}	c_{33}	c_{34}	c_{41}	c'_{41}	c''_{41}	c_{42}	c_{51}
3.1E+05	5.0E+06	9.0E+08	1.0E+06	1.0E+06	1.0E+06	3.4E+07	7.0E+08

Table 9. Comparison between the costs of the two proposed models ($\times 10^9$)

		Natural cost			**Social cost**				**Human cost**			**Passing cost**		**Built cost**
	Debris removal	Debris transporting	Landfill cost	Loss of family members	Asset loss	Market loss	Burial cost	Rescue cost	Medical care cost	Death toll	Authorities involvement cost	Temporary housing cost	Permanent housing cost
Original	11.91	11.91	119.05	6.26	396.84	2976.3	62.57	6.21	67.92	5631.5	47.01	461.89	9509.4
Modified	10.17	10.17	101.7	6.77	339.0	2542.5	67.72	4.17	50.9	6094.9	37.31	341.9	7124.5

Table 9 depicts the differences between the two models when evaluating costs. Even though the differences in the mentioned assets are small, the second model allows one to alter the costs of the mentioned community assets (for cities under study) and observe the resulting consequences.

The costs of the disaster for the original and modified models are 1.9309 e+013 and 1.6732 e+013 respectively, which show a 13 percent improvement.

Having classified the different costs of a seismic disaster, it is now possible to compute the total recovery cost by adding the recovery costs of different community assets. To observe the effect of pre-disaster efforts on post-disaster costs, different budget scenarios are generated by increasing the three budgets of *B*x, *B*y, *B*z: (0-3.5) $\times 10^{11}$, (0-2.5) $\times 10^{10}$, and (0-5.8) $\times 10^{8}$ respectively. Figure 9 is a representation of the budget scenarios, which are illustrated again in Figure 10. Figure 10 depicts the associated recovery costs of each scenario. It is clear in Figure 10 that as the mitigation budget increases, the recovery costs decrease dramatically. Though this change (in the budget) seems small in Figure 10, its consequences on the recovery costs are immense. The first state in the figure (*B*x+*B*y+*B*z = 0) has the highest recovery cost of 5.1×10^{13} (monetary units), and the last state (*B*x+*B*y+*B*z = 3.8×10^{11}) has zero cost of recovery. In the last scenario, enough investment has been allocated to all the three sectors and, therefore, no recovery action is required.

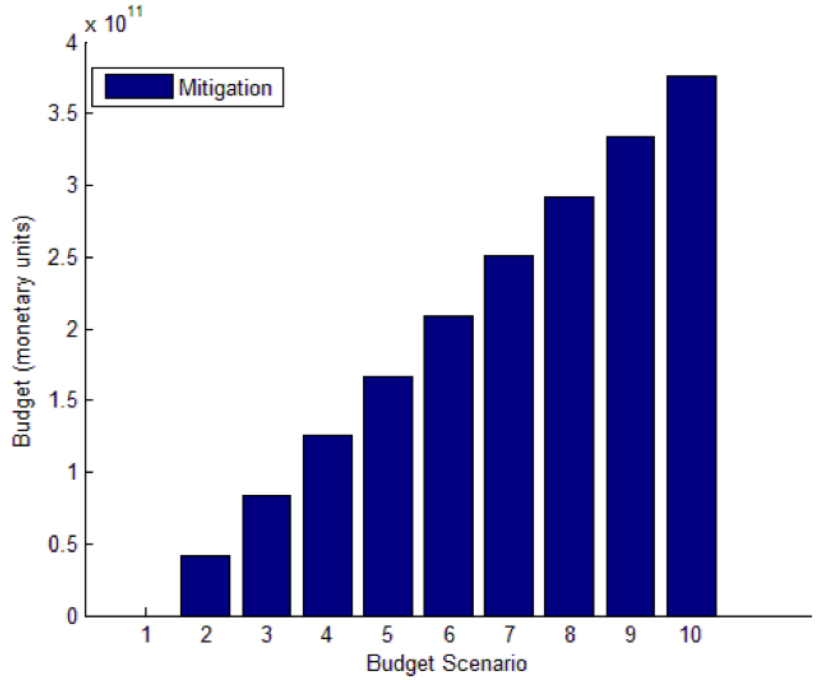


Fig. 9. Ten different budget levels (Bx+By+Bz)

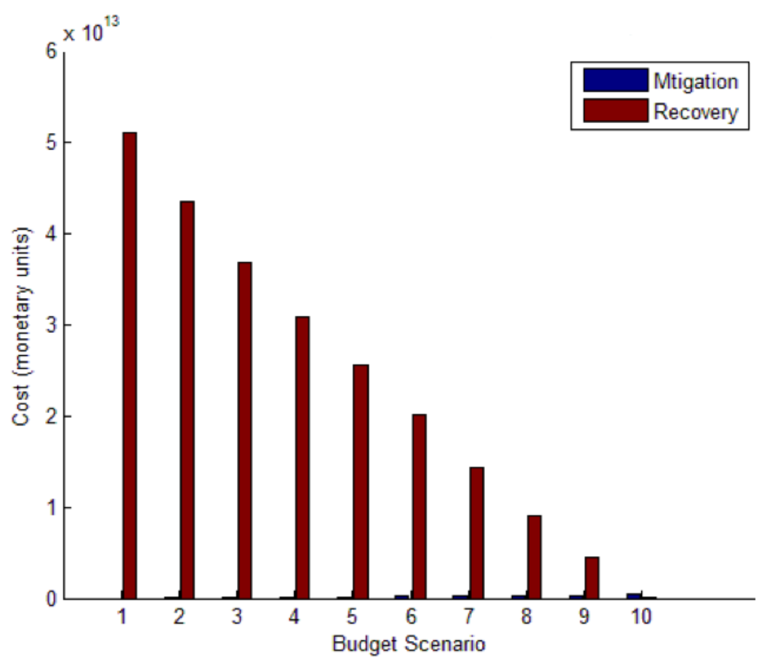


Fig. 10. Effect of the mitigation budget on the cost of recovery

CONCLUSIONS

This article defines the connectedness between the different phases of disaster management, which has been neglected in previous studies. Also, region importance theorem changed and a considerable improvement observed. Although mitigation activities are usually neglected, we illustrate how a minute change in the mitigation budget can enormously affect different assets of a community. In other words, any failure to notice or negligence in the probability of disasters can have unrecoverable consequences. The contribution of this study is to shed more light on the significance of mitigation activities and the effect they have on recovery. Finally, we make the following related suggestions for further research:

1. Identification and integration of other influential agencies in disaster management are of priority concern to account for all the effective forces. One of such agents is the Building Stabilization Agency, which reduces the probability of secondary disasters (e.g. dam failures, fires, etc.) by retrofitting structures after the disaster.
2. Classification of the available resources and capital (such as construction machines; cranes, trucks, dozer, etc.) along with the assigned budgets is necessary. Such classification and allocation of resources to various agents will better bridge the gap between pre-disaster and post-disaster recovery processes.
3. This paper only considers earthquake disasters. This research is the beginning of the modelling of various other types of man-made (e.g. fires, transport accidents, industrial accidents, oil spills and nuclear explosions) and natural disasters (e.g. landslides, volcanic eruptions, floods and cyclones) with consideration of the influential agents.

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APPENDIX

The Proposed Mathematical Model

The model is comprised of a Master Problem (MP) and other sub-problems. The decisions of the primary sectors are outlined by solving three different sub-problems: The Building Renovation Problem (BRP), the Emergency Location/Allocation Problem (ELAP), and the Network Improvement Problem (NIP).

The Building Renovation Problem (BRP)

The availability of values of P_{sl}, q_{sl}, $x^{\mathrm{k,sl}}$, and travel times ($\tau^{\mathrm{k,sl}}$) would declare the term I_{sl}, which is the importance of region *sl*. I_{sl}consists of two terms; the first term ($P_{sl}q_{sl}$) is the population whose life is in danger and the second term stand for the number of people who are saved by means of emergency response ($\sum_k x^{k,sl}{}_c.S(\tau^{k,sl}{}_c)$). The cost of completely stabilizing region *sl* is denoted by (C_{sl}). The objective determines a way to achieve the best outcome by stabilizing areas which constitute greater importance (I_{sl}). There are various scenarios (c) which can happen to the transportation links. Therefore the dispatched emergency supplies $x^{k,sl}$ and the travel times $\tau^{k,sl}$ are dissimilar for various scenarios.

$$(BRP)\ Max_z F = \sum_{sl} I_{sl,c} z_{sl,c} \quad \forall c \in M \tag{A-1}$$

$$\text{S.t. } \sum_{sl} C_{sl}.z_{sl,c} \leq B_z \tag{A-2}$$

$$0 \leq z_{sl,c} \leq 1 \tag{A-3}$$

$$I_{sl,c}=P_{sl}q_{sl} - \sum_k x^{k,sl}{}_c.S(\tau^{k,sl}{}_c) \tag{A-4}$$

in which *M*: is the set of the possible scenarios, and the *BRP*: is solved for each one. Given the probabilistic nature of the problem as regards to *c*, an expected value of Z_{sl} represents the expected future state:

$$\overline{z_{sl}} = \frac{\sum_{c \in M} Pr_c.z_{sl,c}}{\sum_{c \in M} Pr_c} \tag{A-5}$$

where Pr_c: represents the probability of occurrence of state (c). If all the possible scenarios are considered in the solving process, then the dominator of the fraction become one, whereas if some more important scenarios are accounted for, the dominator would be less than one, to account for the relative occurrence probabilities of these (important) scenarios.

By neglecting the effect of the Emergency Location/Allocation Problem (ELAP) in the BRP (ignoring the second term of $I_{sl,c}$ in Eq. (A-4)), we can calculate the values of $\overline{z_{sl}}$. Since we do not yet have the values of $\{x^{k,sl}\, \forall\, k, sl\}$, the solution is initiated by setting this value to zero and solving the BRP.

Emergency Location/Allocation Problem (ELAP)

The location and inventory level of emergency supplies is extremely critical. If situated in positions where high accessibility to affected areas is more likely, fewer lives would be lost. It is vital to formulate the problem such that to maximize the number of rescued individuals within the available related budget. Emergency location/allocation Problem (ELAP) is dependent upon the state of the transportation network after the occurrence of the earthquake, c.

Let λ_k represent the cost of inventory of enough supplies in zone k to save one life. This cost could be influenced by factors such as the available space for inventory, existing emergency vehicles, and others. The amount of previously located emergency supplies in zone k is denoted by w'_k, which is constant. To account for the supply level of emergency supplies, Eq. (A-7) is formed which suggests that the dispatched supplies from zone k are less than (or equal to) the available inventory levels (of zone k). In this constraint, new supplies ($w_{k,c}$) are dependent upon the state c. In Eq. (A-8), we have constrained the dispatched supplies to zone sl to be less than (or equal to) its demand (b_{sl}^{new}). Having solved the BRP earlier, the value of b_{sl}^{new} changes form $P_{sl}.q_{sl}$ to $P_{sl}.q_{sl}.(1-z_{sl})$.

Let R_{gn} be the set of regions in the study area. Then, the ELAP may be written as follows:

$$(\text{ELAP})\text{Max}_{x,w}\text{ELAP}_c = \sum_{sl}\sum_{k}[x_c^{k,sl}.S(\tau_c^{k,sl})] \quad \text{(A-6)}$$

$$\sum_{sl} x_c^{k,sl} \leq w'_k + w_{k,c}\ \forall\ k \in Rgn \quad \text{(A-7)}$$

$$\sum_{k\in Rgn} x_c^{k,sl} \leq b_{sl}^{new}\ \ \forall\ sl \in Rgn \quad \text{(A-8)}$$

$$\sum_{k\in Rgn} \lambda_k.w_{k,c} \leq B_x \qquad x_c^{k,sl} \geq 0 \quad \forall\ k \in Rgn \quad \text{(A-9)}$$

Similar to the BRP, this sub-problem is also solved for every future state. Next, like the BRP the expected value of inventory levels $\overline{w_k}$ is obtained by the following to account for an expected future:

$$\overline{w_k} = \frac{\sum_{c\in M} Pr_c\,.\,w_{k,c}}{\sum_{c\in M} Pr_c} \quad \text{(A-10)}$$

Another sub-problem called the Effective Emergency Response System (EERS) is created. ELAP is solved to find the emergency inventory levels for every zone, and ERRS is solved with a constant value of $\overline{w_k}$, obtained from ELAP, to find the best response, i.e. $x_c^{k,sl}$, for each possible future state, c. The solution of EERS is the actual Emergency Response Plan in case of a disaster, c, given the expected allocation supplies to the locations.

$$(\text{EERS}) \quad Max_x EERS_c = \sum_{sl}\sum_{k}[x_c^{k,sl}.S(\tau_c^{k,sl})] \quad \text{(A-11)}$$

$$\sum_{sl} x_c^{k,sl} \leq w'_k + \overline{w_k} \qquad \forall\ k \in Rgn \quad \text{(A-12)}$$

$$\sum_{k\in Rgn} x_c^{k,sl} \leq b_{sl}^{new}\ \ \forall\ sl \in Rgn \quad \text{(A-13)}$$

$$x_c^{k,sl} \geq 0 \quad \forall\ k \in Rgn \quad \text{(A-14)}$$

Network Improvement Problem (NIP)

Since there is almost never a sufficient budget to retrofit the links of the entire transportation network, it is crucial to detect which links make a larger impact. The cost of completely retrofitting link (i,j) is denoted by C_{ij} , and y_{ij} ($y_{ij} = 0\ no\ action, y_{ij} = 1\ complete\ retrofitting$) declares what portion of link (i,j) is to be retrofitted. The budget constraint for the NIP is demonstrated in (A-16). If the importance of every link $I_{ij}, (i,j) \in A$, is determined, then the NIP would be formulated as the following:

$$(\text{NIP})\ Max_y \sum_{(i,j)\in L} I_{ij}.Q_{ij}.y_{ij} \quad \text{(A-15)}$$

$$\sum_{(i,j)\in L} C_{ij}.y_{ij} \leq B_y \quad \text{(A-16)}$$

$$0 \leq y_{ij} \leq 1 \quad \text{(A-17)}$$

where Q_{ij}: is the probability that link *(i,j)* fails in an incident. Hence, the importance of every network link needs to be acquired.

Link importance of the transportation network

A link is considered important if the reliability of the network is raised distinctly when that link is retrofitted. Here, reliability function is defined as the probability that the ratio of the efficiency of emergency response in a degraded network over the efficiency of the emergency response in the intact network does not reach a certain threshold.

$$R(\theta) = Pr\left\{\frac{EERS_c}{EERS_{c^0}} \geq \theta\right\} \quad \text{(A-18)}$$

where $EERS_c$: is the performance of the Emergency Response when state (c) occurs, $EERS_{c^0}$ is the performance of the Emergency Response when no link fails after an incident, and θ is a threshold level of acceptance (Poorzahedy and Shetab-Bushehri, 2005).

As Poorzahedy and Shetab-Bushehri (2005) note in their study of network performance improvement under stochastic events, an important link in a network is a link such that reducing the probability of the link's failure in an incident would increase the measure of the network performance significantly. To quantify the importance levels of different links, we use $I_{ij} = -dR/dQ_{ij}$, where Q_{ij}: is the failure probability of link (*i*,*j*).

Using the Bayes theorem, the reliability (function) may be written as:

$$R(\theta) = R_{+ij}.\left(1 - Q_{ij}\right) + R_{-ij}.Q_{ij} \quad \text{(A-19)}$$

where R_{+ij}: is the reliability of the network when link (*i*,*j*) always survives, and R_{-ij}: is the reliability of the network without link (*i*,*j*). Thus, the importance of link (*i*,*j*), I_{ij}, may be computed as:

$$I_{ij} = \left(\frac{-dR(\theta)}{dQ_{ij}}\right) = R_{+ij} - R_{-ij} \quad \text{(A-20)}$$

City Disaster Level (CTDL)

When a disaster strikes and the catastrophe state is revealed, it is time to execute the proper emergency response plan (as already obtained by EERS). The disadvantage of not knowing which scenario will happen, forces the decision-makers to minimize the expected value of the CTDL.

$$CTDL_c = \sum_{sl}\{P_{sl}.q_{sl}.(1 - \bar{z}_{sl}) - \sum_k {x^{k,sl}}_c.S(\tau^{k,sl})\} \quad \text{(A-21)}$$

$$\overline{CTDL} = E(CTDL) = \frac{\sum_{c\in M} Pr_c.CTDL_c}{\sum_{c\in M} Pr_c} \quad \text{(A-22)}$$