# Optimized Budget Allocation Model for Earthquake Mitigation in Urban Settlements

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**SUMMARY:**
This paper describes an automated model that uses the output of existing earthquake loss estimation methodologies to support decision-makers in evaluating a set of competing seismic mitigation alternatives and exploring their impact in reducing socio-economic losses of urban settlements. The proposed model is structured to quantify the monetary value of earthquake losses, and to find an optimal budget allocation assigned to each mitigation alternative based on the user input. The system consists of five main modules: (1) building damage module; (2) mitigated damage module; (3) cost estimation module; (4) optimization module; and (5) user interface module. Whereas the optimization module provides the optimal values assigned to each mitigation alternative based on the estimated costs and a defined budget. The outputs of the proposed model are presented with respect to an application in a pilot study area within a vulnerable city district of Tehran, Iran.

*Keywords: Budget allocation, Optimization, Earthquake Mitigation, Loss estimation, Urban Area*

## 1. INTRODUCTION

The city of Tehran is the political, economical and social capital of Iran, and is also located in a very high seismic zone at the foot of the Alborz Mountains. Surrounded by three main active faults; North Tehran fault and Mosha fault to the north, and Ray fault in the plains to the south, the city has suffered large earthquakes in cycles of approximately every 180 years. The last large historical event occurred in 1830, and local seismologists are considering the possibility of a large earthquake in Tehran in the near future (Berberan et al. 2001, Abbasi et al. 1999, Hessami 2003). Different investigators have estimated seismic losses for Tehran and have shown that the occurrence of an expected large earthquake can cause major human and economic losses (Ghafory-Ashtiany et al. 1992, Ghafory-Ashtiany 2001, Ghafory-Ashtiany and Jafari 2003, JICA 2000).

With an estimated population of more than 8 million (13 million in the whole metropolitan area), Tehran has experienced the highest urbanization process of any city in Iran and has undergone a phenomenal growth, particularly since the mid-20$^{th}$ century. The disintegrated and sprawl-like growth of Tehran in recent decades, the absence of appropriate urban planning and effective seismic building codes, particularly in older parts of the city, have left the city considerably vulnerable to earthquakes (Amini-Hosseini et al., 2006). The Tehran master plan for earthquake disaster mitigation (JICA, 2004), points to high population density, unplanned growth of the city, inappropriate design and poor construction of buildings, and inadequately planned urban facilities as the main contributors of vulnerability to a future earthquake in Tehran.

Despite numerous seismic hazard and risk assessment studies carried out for the city of Tehran (JICA 2000, 2004, 2010, Jafari 2005) and proposed mitigation policies for reducing earthquake damage cost (JICA 2004, Hosseini 2006, Amini et al. 2007), an important challenge towards reducing earthquake risk in Tehran is the lack of processes and practices that inherently incorporate results of risk analyses and disaster loss estimations in the key functions of institutions that undertake activities such as land use and urban development planning, construction and building licensing, environmental management, and social welfare (Amini-Hosseini and Jafari 2007, Amini-Hosseini et al. 2009). This requires high-level understanding of the earthquake risk and its impact among various stakeholders and decision-makers, each with their own mandates and priorities. Tools that support decision-makers in using the results of a technical analysis in terms that are meaningful and relevant to their daily operations and functions, can create a better understanding of priorities and opportunities, and ultimately help increase the chances of successful mitigation adoption.

This paper describes the development and components of an automated model that uses the output of existing earthquake estimation methodologies and supports decision-makers in planning appropriate strategies in order to mitigate socio-economic losses of earthquakes in urban settlements. The focus here is to quantify improvement and service costs associated with several mitigation scenarios, and to support the decision maker in planning a mitigation scheme by finding the optimal budget allocation solution. The model is structured to quantify physical and human losses of earthquakes, using previously developed earthquake loss estimation methodologies (e.g. JICA 2000, HAZUS 2003, MAEviz 2009). The model is based on an optimization method which takes into account both the pre- and post-earthquake expenditures, including costs of building upgrades, critical facility enhancement, temporary shelter provision, debris removal, hospitalization and human losses. At this stage, the model does not address indirect social risks such as impacts on vulnerable populations, loss of residence and demographic change, loss of cultural/historical resources, and changes in neighborhood character. The model also does not account for indirect economic impacts such as financial loss of businesses and flow-on effects. The proposed model has been applied for the purpose of re-urbanization of one of the most vulnerable urban areas of the city, located within district 17 of Tehran.

## 2. BACKGROUND

Dodo et al. (2005) has classified previous works in mitigation budget allocation into four main approaches: deterministic Net Percent Value (NPV) analysis, probabilistic NPV, multi-attribute utility models, and optimization models. Deterministic NPV (cost-benefit) analysis, the most straightforward method, consists of: (1) estimating the cost of implementing each mitigation alternatives, (2) estimating the benefit of implementing each mitigation alternatives, (3) comparing alternatives according to one of the equivalent decision criteria: benefit-cost ratio, benefit minus cost, or net present value. Examples of such studies include Altay et al. (2002), Chang (2002), Kappos et al. (2004), and Kunreuter et al. (2001). Stochastic NPV analysis is similar to the previous method except it uses a probabilistic approach instead of a deterministic one. The procedure includes: (1) estimating the cost of implementing each mitigation alternative, (2) estimating probability density function of benefits for each mitigation alternative (where the uncertainty is due to uncertainty in earthquake occurrence), and (3) comparing alternatives according to one or more decision criteria, such as expected value and variance of NVP. In multi-attribute utility models, different factors are taken into account. For instance, Nuti and Vanzi (1998) compare structural upgrading strategies for hospitals based on various performance indices for the response of associated system of hospitals, including, for example, average distance traveled for a casualty, and decrease in number of damaged beds. In the optimization method, contrary to three fore-mentioned methods, there is no need to have predefined mitigation strategies to run the analysis. The optimization method can be used to select a set of mitigation strategies from an existing menu of mitigation alternatives by maximizing the expected NVP, given a constraint such as the limit in the budget. For example, Shah et al. (1992) performed an optimization analysis with a budget constraint to maximize the NVP of an investment to improve 15 buildings at the Stanford University campus against earthquakes, where four different structural mitigation alternatives were considered. Benefits were estimated assuming a deterministic earthquake scenario. Shah et al. also performed a dynamic investment optimization that had three 2-year stages. Dodo et al. (2005) proposed a linear program that selects buildings for mitigation based on mitigation costs and the resulting reductions in reconstruction costs. Vaziri et al (2009) modified Dodo's model and added new features which include: (1) allowing reconstruction to be delayed (at a penalty) if the funds are not immediately available, (2) allowing changes in the structural types during both mitigation and reconstruction period, and (3) including an objective to minimize the chance of an extremely large death toll.

## 3. MODEL DESIGN

A model has been developed to optimize the allocation of a defined mitigation budget for competing mitigation alternatives, and assists the user in prioritizing urban improvement projects by interactively displaying the costs and benefits of each mitigation strategy corresponding to the requirements of the user. The model and all of its components have been developed in MATLAB. The model design integrates previously developed earthquake loss estimation models for estimating building damage, human casualties, displaced households, debris volume, and direct economic losses. A user interface allows stakeholders to interact with the software and define input values for a number of mitigation strategies. These values are used in the optimization model to determine which of the selected mitigation measures is most effective for the given budget limit. The model consists of five main modules: (1) building damage function; (2) mitigated damage function; (3) cost estimation function; (4) optimization function; and (5) user interface function. Figure 1 shows the different modules and the relations among them. In addition to the interactive procedure which takes stakeholder input into account (via the user interface function), the model is designed so that the computations are iterative and converge on an optimal solution. The following will provide a description of the functions and mathematical formulations used in each of the five modules.

*Building Damage Function (BDF)* Damage to buildings is the principle driver used in the proposed optimization model, and all other social and economic losses are computed as a direct consequence of building damage. The building damage function calculates the damage ratio for each damage state (slight, moderate, extensive and complete) based on HAZUS vulnerability parameters.

*Mitigated Damage Function (MDF)* This function modifies the results of Building Damage Function by reducing the damage state values according to the mitigation scenario selected by the decision maker through the User Interface Function. As there is no mitigation scenario provided by the decision maker in the initial model run, a pre-defined mitigation scenario is applied in the initial analysis and MDF calculates damages resulting from this pre-defined mitigation scheme. These damages include: weight of structural debris, injured people count, dead people count, displaced households count and average damage ratio of buildings. In the second model run, the building damage states are calculated according to the decision maker's input on mitigation alternatives that are considered. As building damage is an input to calculating all other damages, these are also calculated as direct consequence functions.

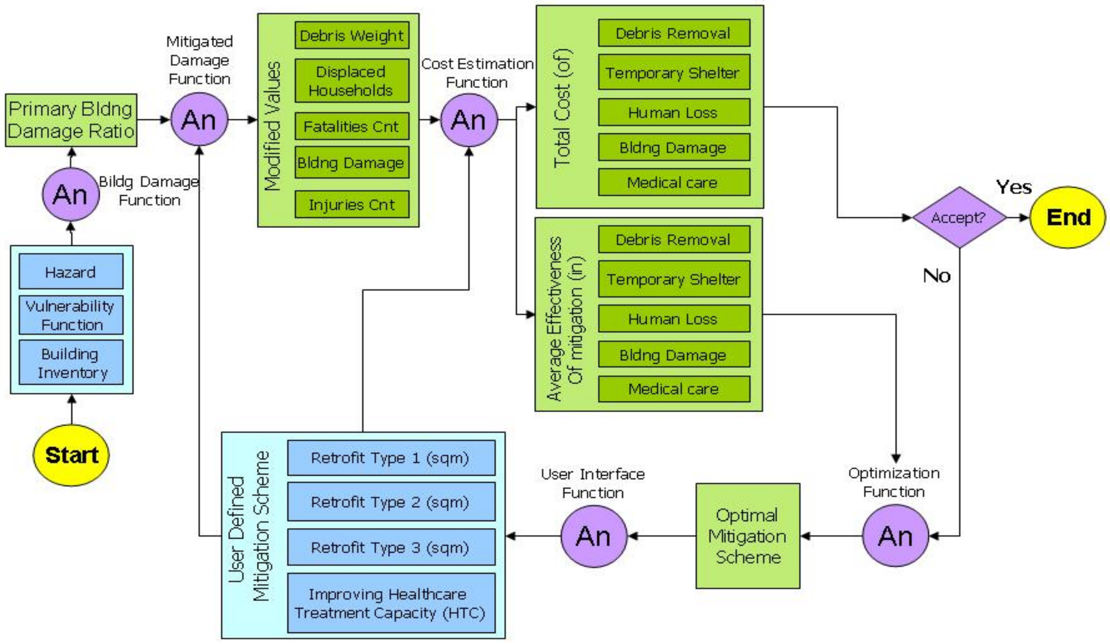


**Figure 1:** General flow chart of model

According to the common guidelines for seismic rehabilitation of buildings in Iran [FEMA 1997, FEMA 2000, Management and Planning Organization 2007], three types of structural retrofit schemes (in terms of building performance levels) have been considered as mitigation alternatives for upgrading the vulnerable: 1) collapse prevention level, 2) life safety level, and 3) operational level. Each of these retrofitting alternatives has its own costs and specification. Buildings improved to the collapse prevention performance level may pose a significant risk of injury, but gross loss of life is assumed to be avoided. It may not be practical to repair the building and it would need to be replaced. For the life safety performance level, injuries may occur during the earthquake; however, it is expected that the overall risk of life-threatening injury as a result of structural damage is kept low and it should be possible to repair the structure. By improving the seismic performance of critical facilities, such as hospitals to an operational level, it is assumed that most of nonstructural systems required for normal use of the building will remain functional and the risk of life-threatening injury as a result of structural damage is very low [FEMA 1997, FEMA 2000].

In the absence of a reliable human casualty estimation function adapted to the conditions of Tehran, casualty estimation in MDF is performed using the results of mitigated damage states values and HAZUS-MH (2003) methodology. Following HAZUS methodology, injuries are categorized into four severity levels: (1) Severity Level 1: Injuries will require rudimentary medical attention but hospitalization is not needed, though injuries should be rechecked frequently; (2) Severity Level 2: Injuries will require hospitalization but are not considered life-threatening; (3) Severity Level 3: Injuries will require hospitalization and can become life threatening if not promptly treated; and (4) Severity Level 4: Victims are killed as a result of the earthquake. The number of displaced household and weight of debris generated from building damage (here only the debris from damage to the structure itself and not its contents is being considered) are also obtained using the HAZUS-MH methodology.

*Cost Estimation Function (CEF)* This function combines damage results from the MDF for two cases of *initial pre-defined mitigation* and *No-mitigation* scheme with corresponding monetary values associated with the cost of replacing/repairing damaged buildings, cost of removing debris from damaged buildings, cost of providing shelter to occupants in collapsed and severely damaged buildings and finally, the cost of hospitalization and human casualty, and calculates the total direct loss of the earthquake. It also estimates the *average effectiveness* of the *initial pre-defined mitigation* scheme by calculating the avoided losses. For the buildings with an average damage ratio less than 50%, the repair cost is equal to the product of building replacement cost and average damage ratio. But for buildings with average damage ratio higher than 50%, it is assumed that a repair operation is not feasible and the building replacement cost should be considered. Since one of the principle benefits of seismic rehabilitation of urban built environments is reducing the expected number of fatalities resulting from an earthquake, the value of avoided human losses should be somehow quantified in cost-benefit analyses. A value of human life calibrated for Iran has been used in the analysis.

In order to estimate the number of indirect fatalities, it is necessary to allocate the available operational hospital beds to the injured people. Injuries that are *not* receiving medical care will deteriorate to a more severe casualty level as a function of the healthcare treatment capacity (HTC) of the hospital and time.

The Cost Estimation Function also computes the cost of providing temporary shelter, after the Sphere Project (2004), which is a global standard for the provision of emergency shelter. Mass care and emergency shelter requirements comprise the commodities (water, food, blankets) and shelter support provisions such as sanitary facilities. The CEF module estimates costs for shelter needs based on the number of displaced persons computed in the Building Damage Function (BDF) (based on HAZUS methodology, HAZUS-FEMA 2003).

*Optimization Function (OF)* This Function uses the results of Cost Estimation Function (CEF) and the mitigation budget, defined by the decision-maker, to find the optimal budget allocation scheme. This scheme supports the decision-maker in allocating the defined budget to each mitigation alternative. The optimization function as given in Eqn. 1 is composed of a linear program which is structured to minimize the total cost of earthquake damage through finding the optimal configuration of the available mitigation schemes.

$$Min \sum_i \sum_j \sum_k \sum_l X_{i,j,k,l} C_{i,j,k,l} - Y_{HTC} C_{HTC} \qquad \forall i, j, k, l \qquad (1)$$

where $X_{i,j,k,l}$ is the floor area ($m^2$) of buildings of structural type *i*, retrofit type *j*, usage type *k*, cost source *l* (which consists of building damage, human loss, hospitalization, debris removal operation, and temporary shelter provision). $C_{i,j,k,l}$ is the average effectiveness cost (US$ per $m^2$) for damaged unit floor area of buildings. $Y_{HTC}$ denotes the level of improved healthcare capacity that is added as a mitigation alternative. $C_{HTC}$ is the average effectiveness of improving hospital treatment capacity as a function of the hospitals organizational and operational capacity and the number of new hospital beds. Additional constraints are considered in optimization formulation as given in Eqn. 2.

$$\sum_{i}\sum_{j}\sum_{k} X_{i,j,k} C^{Mit}_{i,j,k} + Y_{HTC} C^{Mit}_{HTC} \le B_{Mit} \qquad \forall j,k,l \qquad (2)$$

Where $B_{Mit}$ is the total mitigation budget that is defined by the stakeholder and $C^{Mit}_{i,j,k}$ is the mitigation cost for structural type *i*, retrofit type *j*, and usage type of *k*. $C^{Mit}_{HTC}$ is the cost of improving the overall healthcare treatment capacity through organizational or operational interventions.. The constraint of total built floor area in the study region is given in Eqn. 3.

$$\sum_{i}\sum_{k} X_{i,k} = A_{i,k} \qquad \forall k,l \qquad (3)$$

Where $A_{i,k}$ is the total floor area of the buildings. Eqn. 4 is the non-negativity constraint.

$$X_{i,j,k,l}, Y_{HTC} \ge 0 \qquad \forall i,j,k,l \qquad (4)$$

Eqn. 5 limits the maximum possible number of new healthcare treatment capacities to $Y^{Max}_{HTC}$.

$$Y_{HTC} \le Y^{Max}_{HTC} \qquad (5)$$

The result of Optimization Function is the optimal values of floor area (X) for each structural type, retrofit type and usage type of buildings. It also presents the number of optimal new hospital capacity (Y) that will be added to the existing hospitals.

*User Interface Function (UIF)* A user interface function supports the decision-maker in planning the mitigation scenarios by providing the user with two numbers computed by the Optimization Function (OF) to assist in the decision making process: an estimated optimal value that should be allocated for each mitigation alternative, and a maximum bound that should not be exceeded for each mitigation alternative based on the value of the mitigation budget specified by the user. The decision maker is of course free to deviate from these suggested values, however the User Interface Function is intended to provide guidance to the user so that decisions are kept within the optimized budget allocations for the respective mitigation schemes.

## 4. IMPLEMENTATION OF MODEL IN THE PILOT AREA

The city of Tehran is comprised of 22 administrative districts. District 17 of Tehran has been used as a pilot area in previous earthquake vulnerability studies due to its adjacency to the Ray active fault, existence of vulnerable buildings, narrow road network, and inadequate emergency facilities (e.g. hospitals and fire squads).
Although the pilot area is a real urban setting with real inventories, in order to simplify the problem in the model implementation, it is assumed that the pilot area is an isolated island which is self-sufficient at all stages of emergency response, containing all necessary manpower, equipments and machinery for emergency medical care and triage, debris removal process and provision of temporary shelter.

Based on Mansouri et al. (2010), two building type Unreinforced masonry (URM) and Steel frame with unreinforced masonry infill (S5) of HAZUS methodology have been chosen as the representative building types for pilot area due to their similarity to Iranian steel frame and Steel and Brick buildings.
The hazard employed in this investigation includes ground shaking for three different scenario events representing the South Tehran, North Tehran, and Mosha Fault. Besides these three events, a *floating earthquake scenario*, which varies in accordance with soil amplification factor of subsurface soil, has been considered in the analysis. The effect of soil amplification factor has been included in the Peak Ground Acceleration (PGA), which is used as the strong ground motion parameter in this study for its availability from Tehran microzonation studies. Due to slight effect of secondary hazards such as landslides and liquefaction (JICA 2000, Askary et al. 2003) in the pilot area, only strong ground motion is considered. Fire following earthquake (FFE) is also not considered in the model.

The replacement cost for buildings was assumed to be 450 US$/$m^2$ based on average construction price in Tehran in 2009. The cost of improving buildings to collapse prevention, life safety, and operational performance level is assumed to be 22%, 38% and 100% of building replacement cost, respectively. The prioritization criterion for allocating structural retrofit to each building is obtained as the product of average building damage ratio and the built area of that building. This means that buildings with higher fatality risk have priority for being retrofitted. Furthermore as the risk of large (day-time) death tolls in buildings with educational land-use is higher than residential buildings, the priority of receiving the mitigation budget is given to the educational land-use.

It is assumed for each increment of investment of 120,000 USD in improving the physical capacity of healthcare system in the pilot area, one new hospital bed can be added to the total number of available hospital beds [Iranian Ministry of Housing price list in 2009]. The maximum number of additional hospital treatment capacity is limited to 100 due to the limitation of available space in the hospitals of the pilot area. The healthcare capacity is calculated as the product of average structural damage of hospital building and the number of hospital beds in normal situation [Nutti and Vanzi 1998]. The average cost of medical care is about 100 US$/per/night [Iranian Ministry of Welfare and Social Security in 2009], and the cost of a loss of life is assumed to be US$ 400’000 for Iran, according to a local study on the value of statistical life (Lame et al. 2008).

## 5. RESULTS AND DISCUSSION

Table 1 shows the damage cost and fatality counts in the pilot area for four different earthquake scenario before implementation of any mitigating strategy. Two earthquake scenarios of South Ray Fault and Floating caused the highest rate of damages and fatalities.

**Table 1:** Damage cost and fatality counts after scenario earthquakes

| Earthquake Scenario | South Ray Fault | Floating | North Tehran Fault | Mosha Fault |
|---|---|---|---|---|
| Max. PGA (Gal) | 531 | 362 | 246 | 157 |
| Damage Cost (US$) | 1042644 | 586051 | 165143 | 69862 |
| Fatality Count | 1263 | 514 | 25 | 1 |

It can be seen that the budget is first spent on retrofitting hospital buildings, in order to reduce the number of secondary fatality. As the mitigation budget increases, the money flows into structural retrofitting for residential and educational land-use, as well as new hospital capacities. The priority of making new hospital capacities or retrofitting non-hospital buildings differs in each scenario, depending on damage severity and number of fatalities caused by earthquake.

Figure 2 shows the spatial distribution of mitigation plan with a budget of 50 million US$ for 4 different earthquake scenarios. In earthquakes with high rate of fatality, as South Ray and Floating scenarios, reducing the human casualty is the first priority. So for a rather low mitigation budget of 50 Million US$, the optimization model allocates the money to a structural retrofitting type that has the highest effect in decreasing the casualties, which is masonry building type. On the other hand, in earthquakes with low degree of fatality, e.g. Mosha and NTF scenarios, reducing the building damage is the first priority. Therefore, optimization model looks for the most economical way of retrofitting buildings, which is the steel building retrofit.

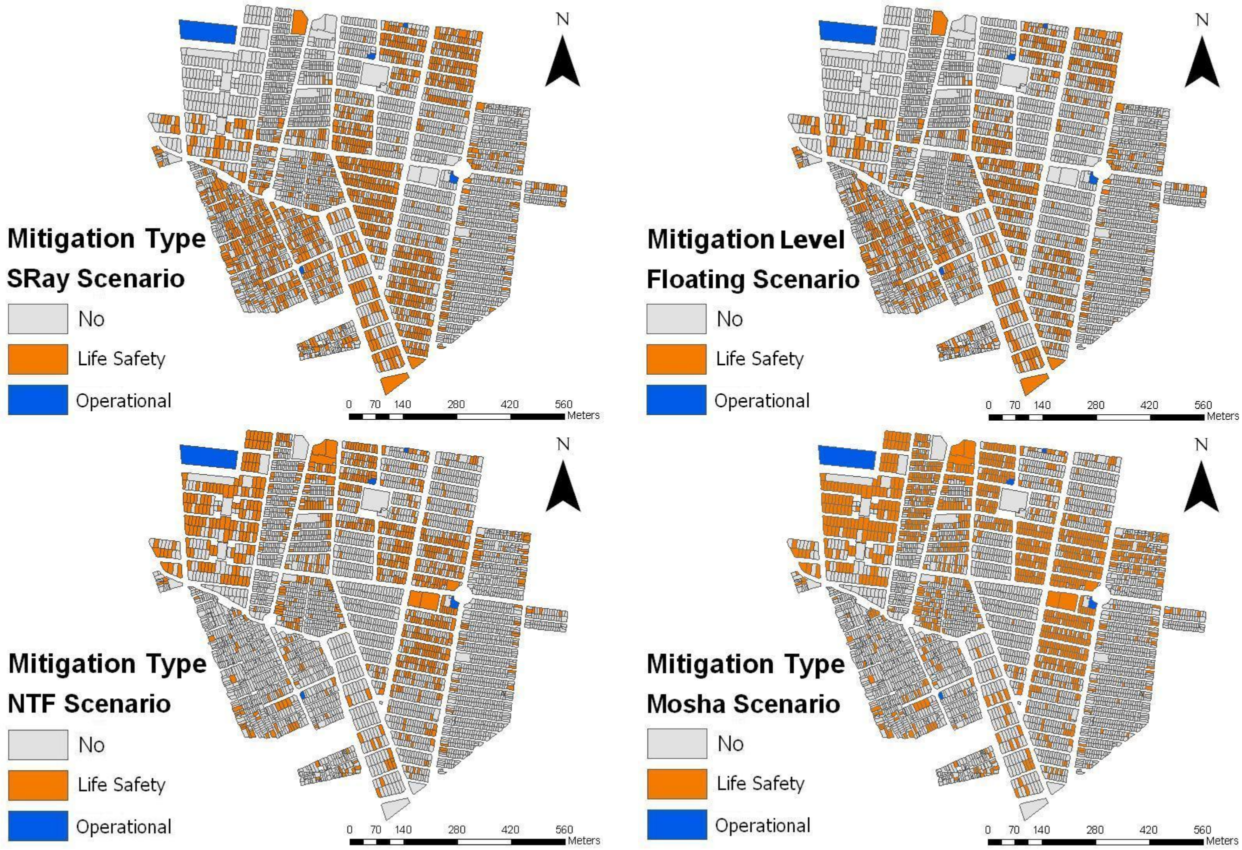


**Figure 2:** Distribution of mitigation alternative in the pilot area for South Ray Fault scenario (2.a Up-left), Floating scenario (2.b Up-right), North Tehran Fault scenario (2.c Bottom-left) and Mosha fault scenario (2.d Bottom-right)

## 6. CONCLUSION

An automated model for optimizing budget allocation in earthquake mitigation scenarios is presented. The proposed model uses previously developed damage estimation, as HAZUS-MH (2003) to calculate different aspects of earthquake damage including building damage, human loss, structural debris weight, displaced households, and finally total direct cost of the earthquake.

In addition, it presents the optimal values for allocating mitigation budget by retrofitting buildings to 3 different seismic performance levels for 3 different usage (residential, educational and medical) and 2 different structural types (masonry and steel-brick), as well as increasing the capacity of medical facilities by constructing new hospital beds. The effectiveness of each mitigation alternative in total earthquake cost is considered through a repetitive process.

The proposed model is developed as a stand-alone application for evaluating cost-effectiveness of several mitigation strategies and allows the decision maker to participate in the process of mitigation planning. The proposed model is different from the similar previously presented models in three ways: (1) it considers a broader source of costs imposed by the earthquake, by considering debris removal cost, and temporary shelter expenditure; (2) it considers the indirect human fatality when there is not adequate medical services for the injured people; and (3) it enters hospital retrofit and new hospital capacities as mitigation alternatives in the analysis. The model computes only the mitigating impact on social and economic losses as a consequence of building damage, but does not consider social and economic impacts from damage to infrastructure (water, gas, electricity, transportation). The current model design also does not consider indirect losses (e.g., business interruption, wages lost, delay in delivery of goods and services, etc.). The model design can be expanded to incorporate methods for computing indirect losses as additional modules and can be upgraded in the future. The automated model has been applied on a study area in Tehran, Iran and spatial distribution of proposed mitigation alternatives is presented. Finally a sensitivity analysis for mitigation budget and the value of statistical human life has been presented.

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