An Earthquake Risk–Sensitive Model for Spatial Land-Use Allocation

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SUMMARY
In recent decades, the agglomeration of population and investment had made the cities more and more vulnerable to natural and man-made disasters. Along with conventional risk reduction alternatives like retrofitting vulnerable buildings, enforcing construction codes, supervising the construction process and increasing the public awareness to earthquake hazard, urban planning in general and land-use management in particular could, as an improving technique, contribute to risk reduction in earthquake-prone urban areas. The model presented here uses the mixed integer quadratic programming (MIQP) to find an optimal spatial land use allocation pattern for a defined urban environment. The proposed model can assist the urban planners with a hazard-informed land-use allocation in planning new urban settlements or in improving existing urban areas in which changing land-use type may impose considerable cost and inconvenience to the administrative sector. As a demonstration of the model performance, it has been implemented in a deteriorated urban neighborhood in 17^{th} district of Tehran city, Iran.

Keywords: Risk-sensitive planning, Land-use allocation, Optimization, Urban risk mitigation

1. INTRODUCTION

In recent decades, rapid global urbanization and rural-to-urban migration has led to a fast un-compatible growth of urban and sub-urban settlements. This agglomeration of population and investment had made the cities more and more vulnerable to natural and man-made disasters. Along with conventional risk reduction alternatives like retrofitting vulnerable buildings, enforcing construction codes, supervising the construction process and increasing the public awareness to earthquake hazard, urban planning in general and land-use management in particular could, as an improving technique, contribute to risk reduction in earthquake-prone urban areas.. Especially in emergency response phase of disaster management, when search and rescue operation, evacuation of homeless people to temporary shelters, fighting the fire following earthquake, are being done, the important role of a hazard-compatible urban planning becomes bolder. Subjects such as location, compatibility and adjacency of land-uses, access to critical urban facilities like healthcare centers and open spaces are directly under urban planning dominance. Dokmeci et al. (1993) presented a generalized land-use model to determine the most efficient utilization of land based on two interactive objectives: (1) Maximization of return; and (2) minimization of the sum of weighted distances among the different land-use units. Aerts et al. (2003) addressed the use of spatial optimization techniques for solving the optimal allocation of multiple sites of different land uses to an area. They solve an MLUA problem using four different integer programs **(**IP**),** of which three were linear integer programs. The IPS were formulated for a raster-based GIS environment and were designed to minimize development costs and to maximize compactness of the allocated land use. They used a weighting factor for preferring either minimizing costs or maximizing compactness. Banba et al. in 2004, focused the land use management planning processes and they divided these processes into three phases: 1) planning background analysis, 2) planning strategy development, and 3) implementation strategies development. They identified factors of each phase and applicable land use control and potential management methods for Marikina City, Philippines. Ligmann-Zielinska et al. in 2008, presented a new multiobjective spatial optimization model, which minimized the conflicting objectives of open space development, infill and redevelopment, land use neighborhood compatibility, and cost distance to already urbanized areas. Tudes and Ygiter in 2010, determined six land use categories of Adana, one of the most earthquake prone provinces of Turkey, by the use of an analytical hierarchical process (AHP) and GSI.

2. MODEL DESIGN

In many studies dealing with conflicting goals or competing stakeholders in land-use allocation problems, specific methods are used to get better insights into possible configurations and their implications for the surrounding areas [Loonen]. One of these methods is spatial optimization: a method designed to minimize or maximize the objectives in spatially explicit studies, given the limited area, finite resources, and spatial relationships between different functions. The proposed model is capable of choosing the optimal spatial pattern of land-uses among several possible alternatives through solving a mixed integer quadratic programming (MIQP) problem which considers boundary conditions. Since the problem involves spatial allocation of land-uses, a raster model of the study area is used. This raster model allows the mathematical core to benefit the topological data of different pixels. Using a raster definition for modeling urban areas enter some uncertainties in the problem. For instance by using a 100m by 100m square pixels, small land-uses are dissolved in main land-uses. Figure (1.5) illustrate the conversion of a real urban land-use pattern to its raster model. It can be seen that small land-use parcels such as roads, commercial and religious are dissolved in main land-uses like residential and green land-uses. As a result, in the proposed modeling, only major land-uses (residential, green space, educational and medical) of the study area are considered. This limitation can be reduced by decreasing the pixel dimensions, which considerably increases the analysis time and makes the problem infeasible. For instance, for a 100 by 100 grid, 50 thousand equations should be solved simultaneously which takes several hours if no convergence error happens. Therefore, for feasibility purposes, a 20 by 20 grid model for study area is considered.

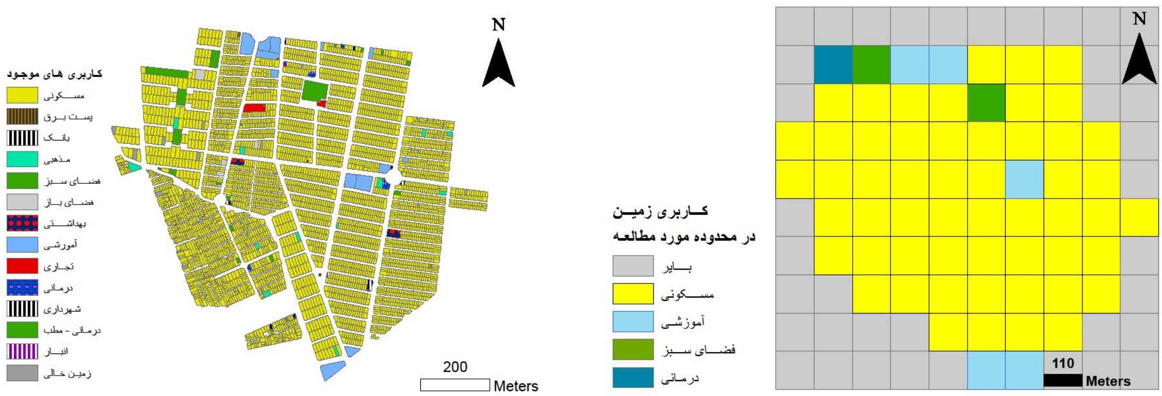

Figure (1.5):converting a vector model of land-uses to a raster model

The goal of the presented model is to optimize a multi-objective problem by using a weighted summation method. The objectives of the optimization are as follow:

Minimizing the susceptibility to earthquake hazard: for reducing the susceptibility of urban inhabitants to the earthquake hazard, the distribution of hazard intensity should be considered in the optimization process. Therefore, the spatial distribution of land-uses could be determined based on the seismic vulnerability of each land-use. For example, in educational land-uses like schools, because of concentration of people, high fatality rate is expected in case of an earthquake. On the contrary, in an open space land-use the likelihood of human loss is basically low. So it may be rational for the more vulnerable land-uses to be located at places with low probability of seismic intensity. In Table (1.5) default normalized importance factors of susceptibility for different land-uses to the seismic intensity are shown. These values were adopted based on experts' opinion.

Table(1.5)*:* normalized importance factors of susceptibility for different land-uses

Land-Use	Residential	Educational	Open space	Healthcare	No land-use
Importance factor	0.4	0.6	0.2	0.9	0

Maximizing the permeability of critical facilities: based on the form of roadway system and width of the roads, permeability of different parts of an urban area could be non-similar. If a road system improving plan exists, the permeability of necessary parts of the city can be increased. In the absence of improving plans, the allocation of the land-use should be done in such way which leads to a better permeability to critical urban facilities like open spaces and healthcare centers. With a better permeability, the possibility of receiving external aids will be enhanced. Table (2.5) shows default normalized importance factors of permeability for different land-uses.

Table(2.5):normalized importance factors of permeability for different land-uses

Land-use	Residential	Educational	Open space	Healthcare	No land-use
Importance factor	0.2	0.4	0.6	0.9	0

Minimizing the average distance to critical facilities: besides providing adequate permeability to critical urban land-uses (healthcare and open space), the average distance to these facilities from demanding land-uses (residential and educational) should be minimized or in other words, the accessibility to those mentioned facilities should be maximized. To attain this objective, a star pattern of proximity was applied. For different accessibility distance, different radius sizes of proximity stars were used. Based on this technique, critical land-uses are assumed to be located in the center of a hypothetical proximity star. The more demanding land-uses (residential and educational) occupy the free places in the proximity star, the more is the accessibility to the central land-use. Fig (2.5) illustrates two proximity stars with the radius size of 1 and 3 pixels.

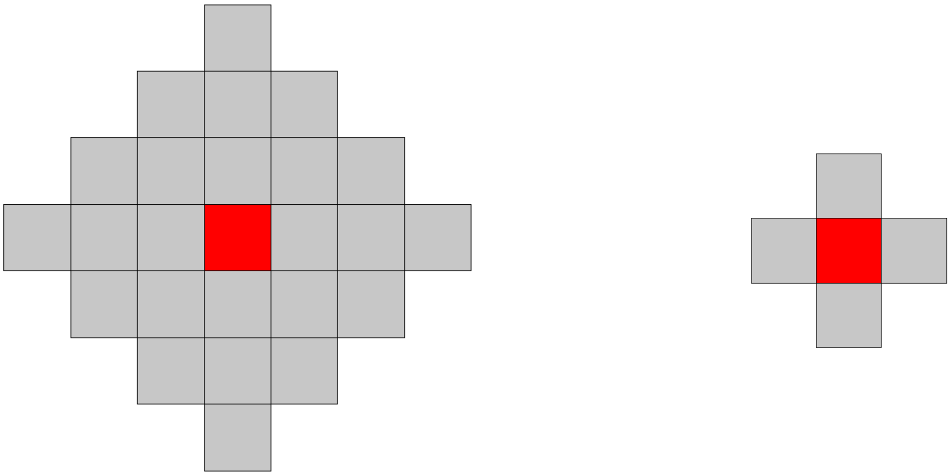

Fig (2.5): proximity stars of different radius sizes

Maximizing the compatibility of adjacent land-uses: adjacent urban land-uses should be compatible in order to reduce the inconvenient effects during both peace time and disaster onset. For instance, healthcare land-use should not be adjacent to residential land-uses, for hygiene considerations. An open space can be a good choice for filling the distance between healthcare and residential land-uses. For attaining this objective, a similar technique, proximity star, was used in the model to prevent incompatible land-uses to be located next to each other. A compatibility matrix was adopted to describe the degree of compatibility of different land-uses as shown in Table (3.5).

Table (3.5): compatibility matrix for different land-uses (1 stands for full compatibility and 0 stands for full incompatibility)

Land-use	Residential	Educational	Open space	Healthcare	No land-use
Residential	1	0.7	1	0.5	-
Educational	0.7	1	1	0.2	-
Open space	1	1	1	1	-
Healthcare	0.5	0.2	1	1	-
No land-use	-	-	-	-	-

Minimizing the redevelopment: By minimizing redevelopment, the change of current urban land use is restricted and therefore only reasonable redevelopment is encouraged. The probability of change of current urban land-uses is determined through using resistance factors. For instance, a low resistance factor for the land-uses which are more reasonable to change, increase the probability of redevelopment for those areas. As a result, by giving open space areas the lowest resistance factor to change, the allocation of other urban uses to these areas is encouraged. The resistance factors for different land-uses are shown in Table (4.5).

Table (4.5): resistance factors for different land-uses

From land-use	To land-use				
	Residential	Educational	Open space	Healthcare	No land-use
Residential	0	1	1o	3	N/A
Educational	1	0	10	3	N/A
Open space	10	10	0	10	N/A
Healthcare	3	3	10	0	N/A
No land-use	N/A	N/A	N/A	N/A	·

3. OPTIMIZATION FORMULATION

Eqn. (1.5) shows the main objective of the earthquake risk-sensitive land-use allocation, which is in the form of the summation of two weighted sub-objectives.

$$\textit{Minimize} \qquad \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M}(w_1 C_{ijk} x_{ijk} + w_2 b_{ijk} x_{ijk}) \tag{1.5}$$

where w_1 and w_2 are the corresponding weights. x_{ijk} stands for the value of the cell (i,j) with the land-use of k. C_{ijk} is importance factor, which is defined as:

$$C_{ijk} = w_H C_{ijk}^H + w_I C_{ijk}^I + w_R C_{ijk}^R \tag{2.5}$$

where C_{ijk}^H, C_{ijk}^H and C_{ijk}^R are importance factors of earthquake hazard, permeability and resistance respectively. w_H, w_I and w_R are their corresponding weight factors. b_{ijk} is adjacency parameter, which is defined as:

$$b_{ijk} = w_A b_{ijk}^A + w_C b_{ijk}^C \tag{3.5}$$

where b_{ijk}^A and b_{ijk}^C are factors of accessibility and compatibility respectively. w_A and w_C are their weight factors. b_{ijk} is the summation of the values within a proximity star and defined as:

$$b_{ijk} = x_{i+1jk} + x_{i-1jk} + x_{ij+1k} + x_{ij-1k} \quad (4.5)$$

Constraints (5.5) ensure that maximally one land use to each cell can be allocated. Eqn. (6.5) guarantees that the demand for land use k is satisfied.

$$\sum_{k=1}^{K} x_{ijk} = 1; \forall i = 1,\dots,N; \forall j = 1,\dots,M; x_{ijk} \in \{0,1\} \quad (5.5)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M} x_{ijk} = T_k; \forall k = 1,\dots,K \quad (6.5)$$

Conditions (7.5) guarantee that the decision variables are binary

$$x_{ijk} = 0; \forall k = 1,\dots,K; \forall i = 1,\dots,N; \forall j = 1,\dots,M \quad (7.5)$$

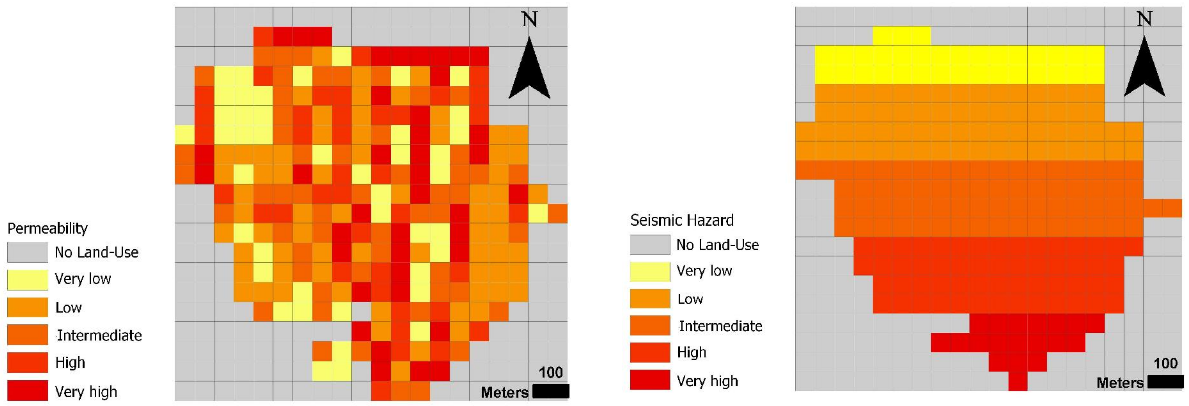

Figure (3.5): spatial distribution of earthquake hazard and permeability in the pilot area

4.RESULTS

The proposed land-use allocation model was applied to a neighborhood in 17th district of Tehran city, Iran. The spatial distribution of the earthquake hazard and permeability of the pilot area is shown in Figure (3.5). The earthquake hazard in the northern region of the area is minimum and it gradually increases to its maximum value in the southern region.

A risk index was used to evaluate the performance of the model for different importance factors. Figure (4.5) illustrates the trade-off between importance factors of earthquake hazard and accessibility. As the accessibility importance factor exceeds the earthquake hazard factor, the land-use pattern takes a more uniform shape n order to provide the maximum accessibility. On the contrary, when hazard importance factor is dominant, all the critical facilities are piled in the upper region where the earthquake hazard is the minimum.

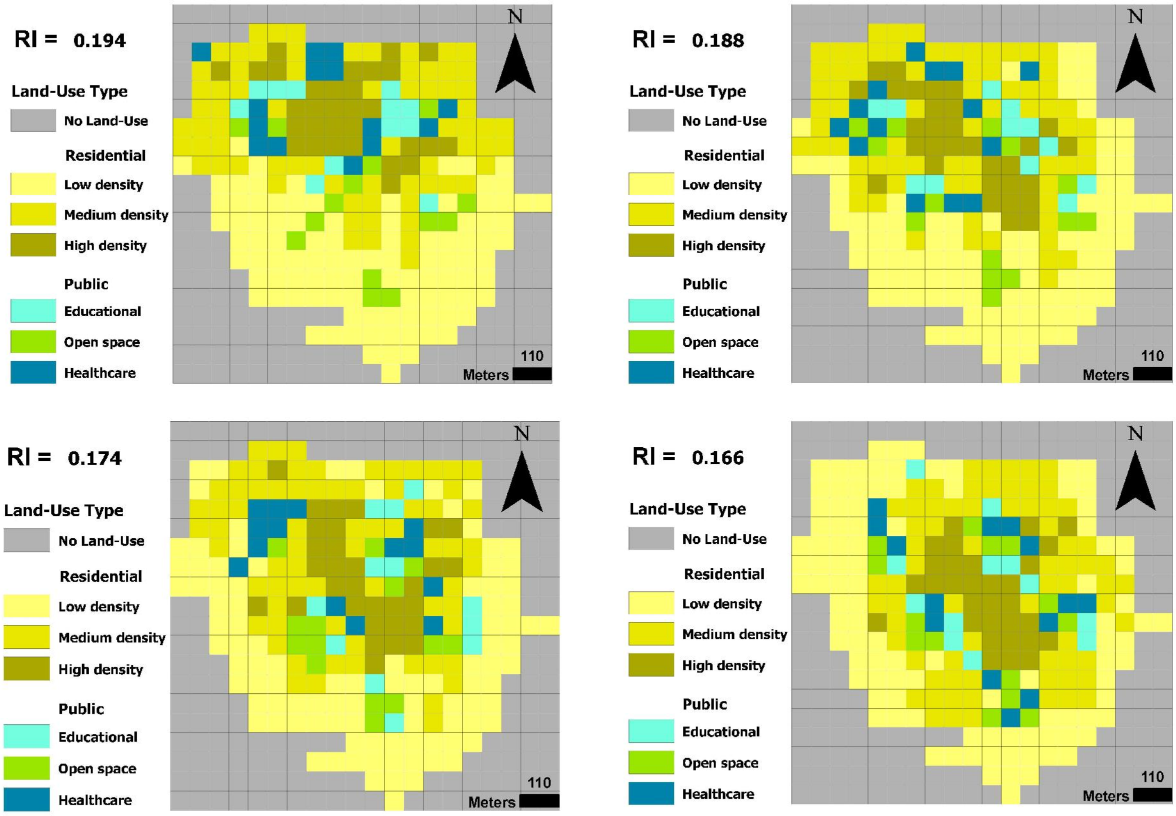

Figure (4.5): changes in land-use pattern due to variation of hazard and accessibility importance factors (the importance factor for accessibility increases from left to right and up to down)

The results obtained from the proposed model were compared to a real land-use allocation done by an urban planner and a random allocation. The automated results have very close risk index values to the real allocation pattern.

5. CONCLUSION

A mixed integer quadratic programming (MIQP) model was proposed to find an optimal spatial land use allocation pattern for a defined urban environment. Considering the standard criteria for land-use planning such as accessibility to public facilities, provision of land-use capacity, compatibility of neighboring land-uses and considering the permeability to the public facilities; the model takes into account the earthquake hazard components. The proposed model was applied to a pilot neighborhood in 17th district of Tehran city, Iran and the results were compared to a man-made LUA pattern and based on the measured risk index values, acceptable performance was observed. The presented model can assist the urban planners with a hazard-informed land-use allocation in planning new urban settlements or in improving existing urban areas in which changing land-use type may impose considerable cost and inconvenience to the administrative sector.

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