A New Approach to Modeling Post-Earthquake Shelter Demand: Integrating Social Vulnerability in Systemic Seismic Vulnerability Analysis

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SUMMARY:
A new approach for modeling demand for emergency shelter and housing caused by earthquake damage which integrates social vulnerability into the modelling approaches is presented. The focus here is to obtain shelter demand as a non-linear consequence of building habitability and social vulnerability of the affected population rather than building damage states alone. The shelter model simulates households' decision-making and considers physical, socio-economic, climatic and spatial factors in addition to modelled building damage states. Social vulnerability conditions are integrated into the framework using Multicriteria Decision Analysis whereby factors including tolerance to loss of utilities (water, gas or electricity) given climatic conditions and a number of socio-economic characteristics influencing the desirability of the building occupants to seek public shelter is accounted for. To operationalize the shelter model, appropriate indicators from the EU Urban Audit Database have been selected using principal component analysis combined with expert judgment. Vulnerability factors deduced from the EU Urban Audit have been validated by applying the model using data from the M 6.3 earthquake that struck L' Aquila, Italy in April 2009.

Keywords: Shelter, Social Vulnerability, Indicators, Multi-Criteria Decision Analysis, Socio-economic Impact

1. INTRODUCTION

For the planning of public shelter provisions in the aftermath of earthquakes the expected number of homeless persons and people seeking public shelter is an essential input for emergency managers. Few models exist that estimate the displaced or homeless population and the number of displaced persons seeking public shelter in an earthquake. Most Earthquake Loss Estimation software providing input for shelter needs are based on the HAZUS methodology which computes both displaced persons and shelter demand as a linear consequence of building damage. For example 90% of all occupants in severely damaged multi-family homes and 100% of all occupants in extensively and completely damaged multi-family and single-family homes are assumed to be displaced according to the HAZUS model default conditions (FEMA, 2003).

Looking at data from 457 historic earthquakes from 1900-2012 with destroyed or heavily damaged building data in the CATDAT Damaging Earthquakes Database (Daniell 2003-2012, Daniell et al., 2011), a linear trend (on a logarithmic scale) of displacement and building damage can indeed be observed (Figure 1). This data shows that the number of displaced persons is generally a little less than one order of magnitude larger than the number of destroyed or severely damaged buildings. However, the data in Figure 1 also shows that in many past events the number of displaced persons is much larger than can accounted for only through the number of occupants in severely damaged or collapsed buildings. Observations from past earthquake events found in the literature show that the number of displaced persons after an earthquake not only depend on external factors like building damage, loss of utilities, and weather conditions but also from household internal socioeconomic and individual factors such as safety concerns or fear of aftershocks (Khazai et al., 2011). The intention to leave can also be undermined through feasibility restraints, e.g. if the next shelter is too far away, if people are disabled or lack mobility. Even if households decide to leave their homes the final question is where they will find accommodation. Alternatives to public shelter are for example to stay with friend and family or in hotels. Thus, only a subset of the total population should be considered in computing demand for public shelter.

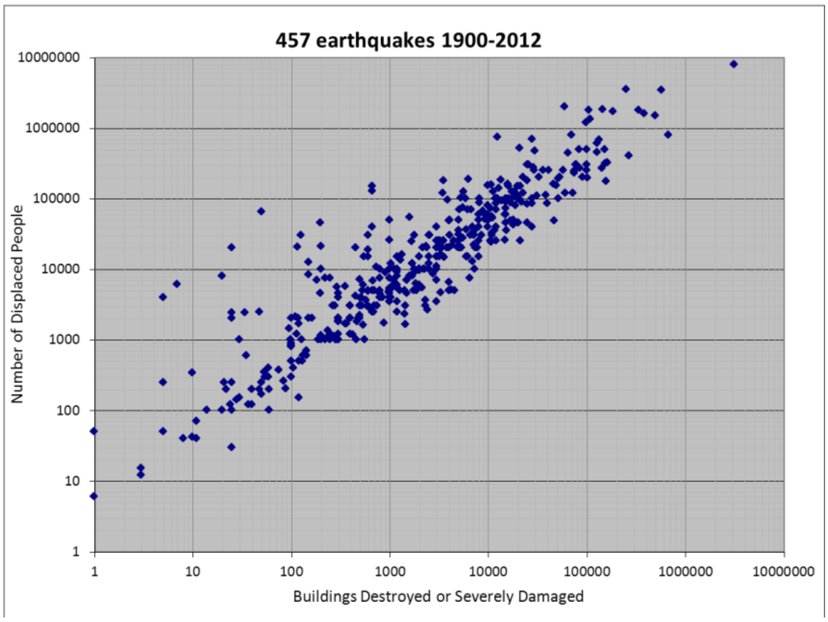

Figure 1 Relationship between severely damaged and destroyed buildings and displaced persons after earthquakes (n = 457 earthquakes from 1900-2012)

Figure 2 shows displaced persons vs. building damage data for major Italian events from 1900 – 2012. As in Figure 1 it can be observed that generally the number of homeless persons is about one order of magnitude larger than the number of severely damaged or destroyed buildings. For many of the events, however, some extra effects can be observed which can be attributed to environmental or socio-economic conditions influencing the displacement behavior. For example, the Friuli earthquake in May 1976 created large-scale devastations, but there was no mass flight from Friuli. Several hundred tremors, aftershocks and the heavy rain that set in immediately after the quake destroyed the already badly damaged buildings and overwhelmed the resistance of the mountain population. When in September of the same year, another strong earthquake struck the Friuli area just before a strong winter set in the psychological effects were much worse on the population and a great exodus from the afflicted area began and many people evacuated to the Adriatic Coast (Geipel 1982). Without the heavy rainfalls after the first quake and the upcoming winter, the number of homeless people would have been substantially lower and closer to the proportion expected from damaged buildings.

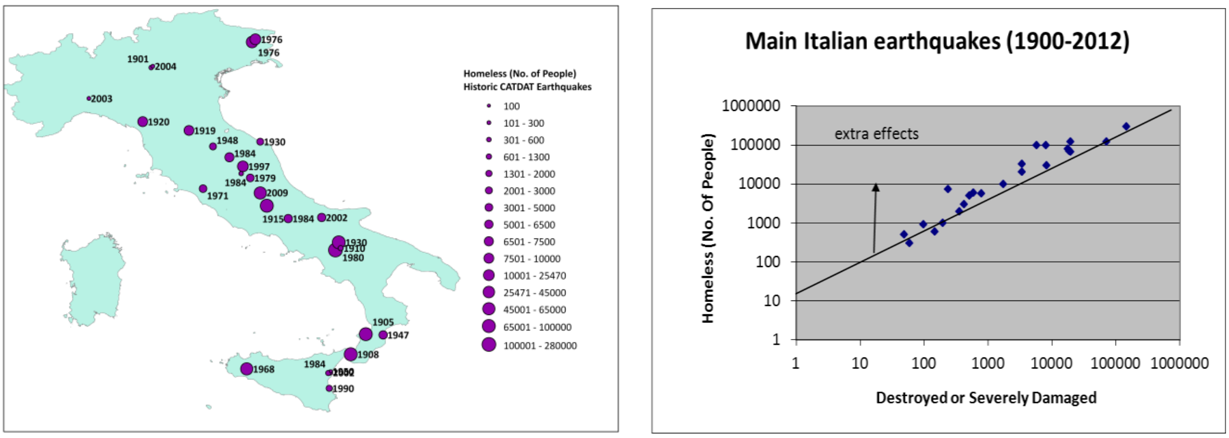

Figure 2 Relationship between displaced populations and number of damaged buildings in main Italian earthquakes (n = 29 earthquakes from 1900 – 2012).

2. SHELTER DEMAND MODEL

Poor linkages between damage to physical systems and resultant social consequences remain a significant limitation with existing hazard loss estimation models (Bostrom et al, 2008). Most Earthquake Loss Estimation software providing input for shelter needs are based on the HAZUS methodology where the displaced population (determined only from building damage) is multiplied by a factor that considers age, ownership, ethnicity and income to determine demand for public shelters. These four parameters were originally developed by the American Red Cross and were based on expert opinion along with historical data from the 1994 Northridge earthquake (Harrald et al. 1992). New approaches have recently been developed which simulates households' decision-making in seeking shelter and considers socio-economic, temporal and spatial factors in addition to housing damage and lifeline loss to estimate displaced and shelter seeking populations (Chang et al., 2009; Wright and Johnston, 2010, Khazai et al., 2011). For example, the model by Chang et al. (2009) adopts an agent-based approach that utilizes census microdata on households and simulates households' decision-making about post-earthquake shelter on the basis of their dwelling condition, risk perception, mobility, and resources.

A new approach is presented for modeling emergency shelter demand by integrating shelter-seeking logic models into a systemic seismic vulnerability analysis and earthquake loss estimation software tool. The selection of socio-economic vulnerability indicators and other factors in the shelter logic model are based on an in-depth literature survey of historic earthquakes and are derived and validated using statistical models. Thus a new advancement to shelter estimation methodology is being explored through three types of key inputs: (1) the "habitability" of buildings which combines inputs from the physical models (building usability, utility loss and climate factors) to provide information on the habitability of a building and can be used as a better determinant in influencing the decision to evacuate than building damage alone; (2) GIS-based shelter accessibility analysis as an input to the shelter seeking model – not discussed in this paper ; and (3) a multi-criteria decision model and for implementing a shelter-seeking logic model based on complex socio-economic factors which ultimately lead to the decision to evacuate and seek public shelter. These three inputs are combined into a dynamic shelter model and software tool developed within the MAEVIZ platform to provide stakeholders an interactive framework in decision-making process for shelter planning and preparedness as well resource allocation.

2.1 Building Habitability

The first step in the decision to evacuate after an earthquake is based on the structural stability of a building and functional lifeline structures, such as access to water gas and electric power services. Weather conditions can further aggravate potential displacement from damaged buildings with disrupted lifeline services. If a building is only slightly damaged and it is very cold and there are no possibilities to heat, that home will be uninhabitable. During other seasons and weather conditions the same building might be habitable. In a rare study surveying post-earthquake survivors about their shelter preferences, Chien et al. 2002 found evidence that under normal weather conditions 67% of the interviewees after the 1999 Chi-Chi Earthquake chose to stay in nearby open fields or make a tent, whereas under wet or cold weather conditions only 17% showed a preference of staying there. Likewise cold weather played a major role in the choices of occupants sought shelter in both of the last two major earthquakes: 2011 Tohoku earthquake (Khazai et al., 2011; Daniell et al., 2011) and the 2012 Van earthquake in Turkey (Wenzel et al., 2012).

Building habitability is determined as a combination of the functionality of buildings (building usability), utility services and impending weather conditions and constitutes the first decision step in leaving or staying at home after an earthquake. Building *usability* is derived from a simplified semi-empirical approach as a function of severity of observed damage to structural and non-structural elements of buildings. The usability model was developed based on a detailed survey of 305 buildings in the densely packed suburb of Pettino obtained from the Italian Department of Civil Protection after the 2009 L'Aquila earthquake. The six usability classes considered during the survey were reduced in this model to just three: buildings which are immediately *non-usable* (*NU*), *partially usable* (*PU*) or *fully usable* (*FU*). Using the Pettino database, Usability Ratios (UR) for buildings were derived for each of the three usability classes as a function of the damage data, reported according to six damage states DS0 to DS5, which were also reduced to three damage states (none, yield, collapse). Usability ratios can be used then to estimate the number of persons in each of the three building usability classes (N_{FU}, N_{PU}, N_{NU}). Using the Usability Ratios in Table 1, the number of persons in each of the three building usability classes can be obtained using the following expression:

$$\mathrm{N}_{FU\ or\ PU\ or\ NU} = \sum_{i=1}^{3} N_i \cdot NO_i \cdot UR_{i.FU\ or\ PU\ or\ NU} \quad (2.1)$$

where:

- i = damage level (i = 1, …, 3)
- N_i = number of buildings having damage level i,
- NO_i = number of occupants (at the time of the event) in each building for each damage level i,
- UR_i = usability ratio (UR) for damage level i for each usability class

Table 1 Empirically-derived Usability Ratios

UR	Damage state		
	None	Yield	Collapse
FU	0.87	0.22	0.00
PU	0.13	0.25	0.02
NU	0.00	0.53	0.98

To determine building *habitability* the usability of buildings is considered together with utility loss in a systemic seismic vulnerability analysis (Cavalieriet al., 2012). Non-usable buildings (*NU*) are also non-habitable. If a building is fully or partially usable, depending on the level of residual service in the utilities and the prevailing weather conditions at the time of impact, it can be habitable (*H*) or non-habitable (*NH*). For each utility, the level of residual service is satisfactory when the Utility Loss (UL), defined as one minus the ratio of satisfied to required demand, is lower than a threshold value ($UL_i < UL_{Ti}$). The threshold values depend on Weather conditions and Building Usability and due to the subjective nature of perceptions, the Utility Loss Threshold (UL_{Ti}) should be established on a context-specific basis by the analyst. The total Utility Loss is a weighted average of UL_i on each of the utilities, with weights w_i provided by the analyst:

$$UL = \sum_{j=1}^{N_{UN}} UL_j \cdot w_j \quad (2.2)$$

where:

- j = utility systems (j = 1, …N_{UN} with N_{UN} = 2 in this application)
- UL_j = Utility Loss in system j
- w_j = weight associated with the importance of loss in utility system j in making the building uninhabitable

The percent fully or partially usable buildings that are non-habitable (NH_{FU} or NH_{PU}) is thus determined as the portion of buildings which have utility losses greater than the utility loss threshold value ($UL \geq UL_T$). The Uninhabitable Building Index (UBI) is computed as the ratip of occupants of buildings that are uninhabitable to the total population (N) according to the following relationship:

$$BHI = (N_{FU}NH_{FU} + N_{PU}NH_{PU} + N_{NU} - N_d)/\,N \quad (2.3)$$

where:

- N_{FU} , N_{PU} , N_{NU} = number of occupants in buildings that are fully, partially and non-usable
- NH_{FU} = percent fully usable buildings that are non-habitable, where UL ≥ ULT
- NH_{PU} = percent partially usable buildings that are non-habitable, where UL ≥ ULT
- N_d = number of dead persons estimated in a selected casualty model

2.2 Shelter-Seeking Decision Model

The basic elements of the logic model for the shelter demand model are based on the ideas of Chang et al. (2009). The shelter model combines each of the decision steps (represented as an output indicator) shown in Figure 3 in a weighted multi-criteria decision analysis framework according to the following scheme: D1 is given by an output indicator as the proportion of population residing in uninhabitable buildings criteria; D2 and D3 are a combination of a number of internal and external factors and given by an output indicator representing the desirability to evacuate criteria; D4 is given by an output indicator representing the desirability to seek public shelter based on the access to resources criteria.

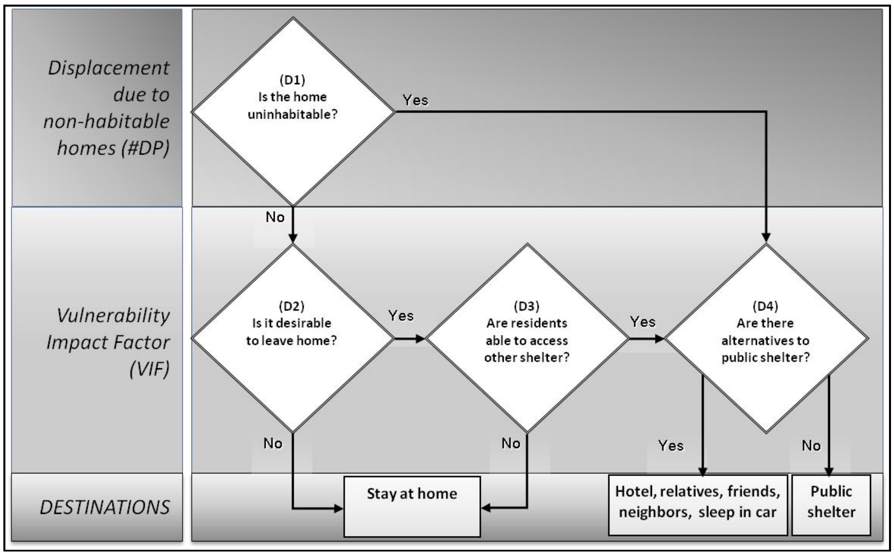

Figure 3 Proposed model framework for the Shelter Seeking Population Index

The decision to evacuate one's home after an earthquake and to utilize public shelter is correlated with a variety of social and demographic factors (Tierney, Lindell and Perry 2001). These decisions are also usually made at the household level; however, as was seen in the case of the L'Aquila earthquake the decision to evacuate can also be imposed by government authorities that make an evacuation of homes mandatory. A survey of disaster literature regarding post-earthquake sheltering demand provided an initial basis for selection of relevant socio-economic indicators related to the desirability to evacuate (Khazai, et al., 2012; Braun, 2011). The main factors influencing evacuation behavior were derived from 18 key studies and are shown in Figure 4. Factors such as income, age and minority status received the most nominations; whereas factors such as race and ethnicity have been dissected thoroughly by US researchers, these were considered as one factor "belonging to the minority" within this model. Other factors such as proficiency of English language - one of the indicators of the Social Vulnerability Index (SoVI) (Cutter, 2008) - also apply to the particular context of the United States or other primarily English speaking countries and were not adopted in this model.

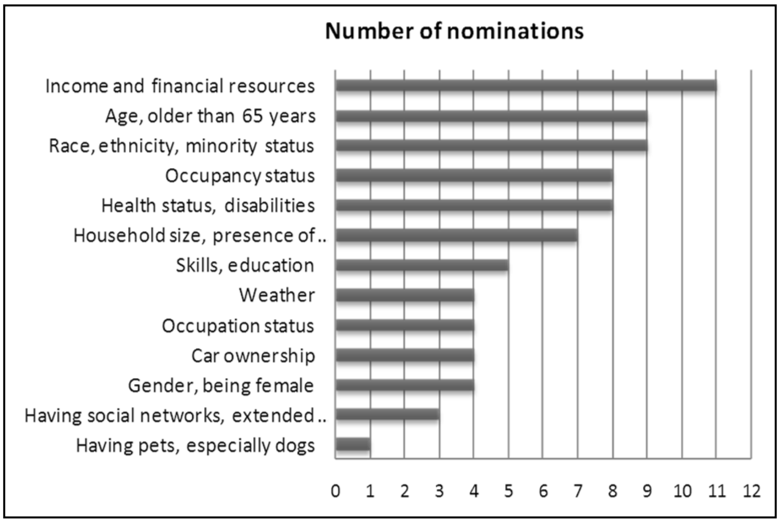

Figure 4 Number of nominations found for indicators in the 18 studies surveyed.

While the literature survey provides for a comprehensive wish list of indicators, an important requirement for operationalizing the approach is that it should possible to quantitatively populate the socio-economic indicators based on an approach that can be harmonized at the European level for the urban scale of analysis; one of the aims of this study. As such, data was compiled from the EUROSTAT Urban Audit for European cities at the sub-city districts (SCD) level and used as a next step to pre-select the most relevant indicators from the Urban Audit that were found in the literature survey. In order to narrow down the selection of the most influential indicators from the Urban Audit and to assign a set of default weights a factor analysis was conducted with the Urban Audit data. Out of the 338 indicators described in the Urban Audit, data is available for only 44 indicators at the SCD level. The 44 indicators were analyzed for two periods: 1999-2002 (7856 districts in 321 cities in 30 European countries); and 2003-2006 (2972 districts in 173 cities in 24 European Countries). Principal component analysis (PCA) was used to calculate the inter-correlation between variables and a new set of transformed variables was created where the importance of each of the new variables in terms of the variability of the data is identified. It was found that close to 75% of variation in data is represented by 8 dimensions shown in Table 2. Additionally, the PCA provides a possibility to model the relative influence of each data in terms of their explanatory power (i.e., how much of the statistical variation can be explained by each indicator).

Table 2 Results of Principle Component Analysis of Urban Audit Data

No	Subjective Factors	Strongest correlated indicator	Strongest correlation value
1	Mortality/Age	Mortality rate for <65 per year	-0.88
2	Education	Prop. of working age population qualified at level 3 or 4 ISCED	+0.77
3	Lone Parent with Children	Prop. of households that are lone-parent households	+0.68
4	Population Density	Population density: total resident pop. per square km	-0.64
5	Migration/Ethnicity	Proportion of Residents who are not EU Nationals and citizens of a country with a medium or low HDI	+0.58
6	Gender	Proportion of females to males in total population	+0.51
7	Unemployment	Unemployment rate	-0.54
8	Sub-standard Housing	Proportion of dwellings lacking basic amenities	+0.67

The literature survey and the statistical models provide a set of candidates for operationalizing the shelter-seeking decision model presented in Figure 3. The first step (D1) is determined through the building habitability analysis as discussed above. The following presents the methodology and indicator framework related to desirability to evacuate (D2 and D3) and desirability to seek public shelter (D4).

2.2.1 Desirability to Evacuate

The desirability to evacuate is a combination of factors related to a set of internal factors which is a reflection of perceived security and safety, as well as external factors forcing residents to leave. Feeling safe at home (or the feeling that it is safer to leave) is subjective and depends on a large range of factors each with different perceived importance values and cultural contexts. As mentioned above the perception of weather conditions is compound with the building damage and utility services disruptions. The resistance to evacuation is also influenced by sociological and economic factors, like having strong social networks, belonging to a minority or being disabled, having enough knowledge and financial resources to protect yourself, and knowing where to obtain information. Other factors influencing the perceived security are conditions such as fear and anxiety of aftershocks or mistrust in safety evaluation of home (green, yellow and red tags) which are more difficult to describe and define quantitatively through indicators. Thus, the desirability to leave is a combination of a complex set of social factors and is ultimately determined by the individual's perception of the importance of each one of these factors in driving the decision to evacuate. While desirability to leave represents an internal driver to evacuation, the resistance to evacuation is also driven by external decisions imposed on the affected population which in some cases may force them to evacuate (e.g., mandatory evacuation of the entire city center as in 2009 L'Aquila earthquake, or radiation advisory and evacuation radius as in the aftermath of the 2011 Tohoku earthquake and tsunami).

$$DE = EF \times \sum_{i=1}^{n} w_i \cdot I_i \quad (2.4)$$

where:

- DE = Desirability to evacuate
- w_i = overall weight given to each indicator
- I_i = indicators representing the desirability to evacuate
- EF = External Factors, derived from a GIS analysis and/or different evacuation scenarios

Table 3 Urban Audit Indicators influencing Desirability to Evacuate

Decision Factors	Urban Audit Indicators for Desirability to Evacuate
Household Tenure (Owner vs. Renter)	-Prop. of households living in priv. rented housing -Proportion of households living in owned dwellings
Housing Type (Single, Multi-family)	-Number of houses per 100 apartments -Proportion of households living in social housing -Proportion of Dwellings lacking basic amenities -Proportion of non-conventional dwellings
Household Type (Large Families with Children, Single Parents)	-Avg. Size of households -Lone-parent households with children aged 18 or under -Proportion of households living in social housing
Age (Children and Elderly)	-Proportion of total population aged 0-4 -Proportion of total population aged 75 and over
Perceived Security	-Total Number of Recorded Crime per 1000 population

2.2.2 Desirability to Seek Public Shelter

Not all displaced population will seek public shelter, and some may find alternative shelter accommodations (rent motel rooms or apartments), stay with family and friends, or leave the affected area. For estimations of shelter demand it is necessary to account various factors that lead to populations seeking public shelter. Desirability to seek public shelter in this study is given by an indicator model related to the "Access to Resources" which accounts for both "push" factors (such as low income, lack of mobility or having no social networks) and "pull" factors (such as being too far from the shelter sites). The "push" factors are determined in terms of socio-economic drivers, while the "pull" factor is an input from a GIS-based shelter accessibility model (Khazai, et al., 2011a). The question of accessibility relates mostly to residents who are able to choose between different destinations. The proximity and ease of access of shelter locations might be a key criteria for these households whose decision of leaving is not founded on aspects of vulnerability but on individual preferences. The Shelter Seeking Index (SSI) is then then derived as an additive weighted sum of the each of the indicators constituting the shelter seeking population and multiplied by how accessible each of the designated shelter sites are, according to:

$$SSI = AI \times \sum_{j=1}^{n} w_j \cdot I_j \quad (2.5)$$

where:

- SSI = Shelter Seeking Index
- w_i = overall weight given to each indicator
- I_i = indicators representing shelter seeking population
- AI = Accessibility Index, derived from a GIS distance-cost analysis to shelter sites

Table 4 Urban Audit Indicators influencing Desirability to Seek Public Shelter

Decision Factors	**Urban Audit Indicators for Shelter Seeking Index**
Income	-Percent of households with less than 60% of national median annual disposable income -Proportion of households reliant upon social security
Unemployment	-Unemployment rate
Migration/ Ethnicity	-Number of residents born abroad (not only nationals) -Residents who are not EU Nationals and citizens of a country with a medium or low HDI
Education	-Prop. of working age population qualified at level 1, 2, 3 4, 5 and 6 ISCED

2.3 Multi-criteria Shelter Model

The integrated shelter needs model developed here is based on a multi-criteria decision theory (MCDA) framework which allows the bringing together of parameters influencing the physical inhabitability of buildings, with social vulnerability (and coping capacity) factors of the at-risk population to determine as well as external factors to determine the desirability to evacuate and seek public shelter. As shown in Figure 5, the mutli-criteria framework can be described schematically as composed of the two main criteria: overall population at risk of being displaced after an earthquake (DPI) and the proportion of this population likely to seek public shelter (SSI). Subsequently, the total demand for public shelter for a particular location (i.e., city district) can be described as a product of the population at risk of being displaced (D1, D2 and D3) to the population likely to seek public shelter (D4). This can be expressed by the equation below where w_{DPI} and w_{SSI} are the weights assigned to DPI and SSI, respectively:

$$SNI = w_{DPI} \cdot DPI + w_{SSI} \cdot SSI \tag{2.6}$$

where, SSI is derived from a weighted index related to lack of access of resources indicators in a community or neighborhood, and DPI is given as occupants in uninhabitable buildings amplified by external and internal factors related to desirability to evacuate according to the following expression:

$$DPI = BHI\ (1 + DE) \tag{2.7}$$

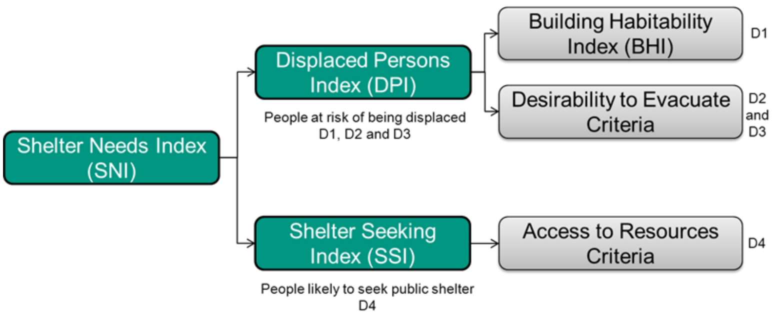

Figure 5 Decision criteria for computing Shelter Needs Index (SNI)

3 MODEL IMPLEMENTATION IN L'AQUILA

To demonstrate the shelter methodology it has been applied to the 2009 L'Aquila earthquake, where detailed data on post-earthquake *Building Usability* (AEDES Survey of 1667 buildings); *Socio-economic* data for 106 fractions (ISTAT data); and *Shelter Population* data from April to August 2009 for 107 shelter sites (Italian Civil Defense) was used to validate the model (Elefante et al., 2011). An open-source multi-criteria decision analysis software was developed to implement the methodology, and was integrated into the MAEVIZ earthquake loss estimation tool. The tool will allow stakeholders to display the Shelter Needs ranking of different neighborhoods using various output and visualization formats. The user can assign and different importance (weights) to selected indicators and the tool can be used to discuss the weighting outcomes and interactively examine the variability of shelter demand in different areas to different weighting schemes, or to different earthquake scenarios.

The rankings for shelter demand after the L'Aquila earthquake are shown in Figure 6 for the 8 Mixed Operations Centers (COM) which had the overall coordinating role in their own territories for all rescue and shelter provision operations. First the Displaced Persons Index (DPI) is obtained as the number of occupants living in uninhabitable buildings (BHI) amplified by the Desirability to Evacuate Criteria (Figure 6c). In this case, the proportion of persons in uninhabitable buildings was not modeled following the methodology and taken directly based on observed values of partially usable and non-usable buildings in each of the 8 COMs from the AEDES Survey. Furthermore, in the calibration of the shelter model people living in the historical city center were recommended to evacuate without consideration of unique building stability due to historical buildings and narrow alleys. Accordingly, the Desirability to Evacuate criteria accounts for forced evacuations in COM1, 2 and 5 (Figure 6b).

To obtain the Shelter Needs Index shown in Figure 6f, the Desirability to Seek Shelter Indicators (Figure 6d) were obtained and amplified based on accessibility to shelter sites in the 8 COMs (Figure 6e). Finally, the Shelter Needs Index (SNI) is obtained as the interaction between Displaced Persons Index and the Shelter Seeking Index (SSI). Figure 5 shows how the modeling approach can be used to capture the actual shelter demand conditions (given as the observed number of people in shelter camps normalized by total population in each COM). For example, based on building usability alone COM 3 should have a lower shelter demand than COM 6 and 4. However given the high desirability to evacuate and seek shelter based on socio-economic indicators, COM3 obtains a more realistic ranking.

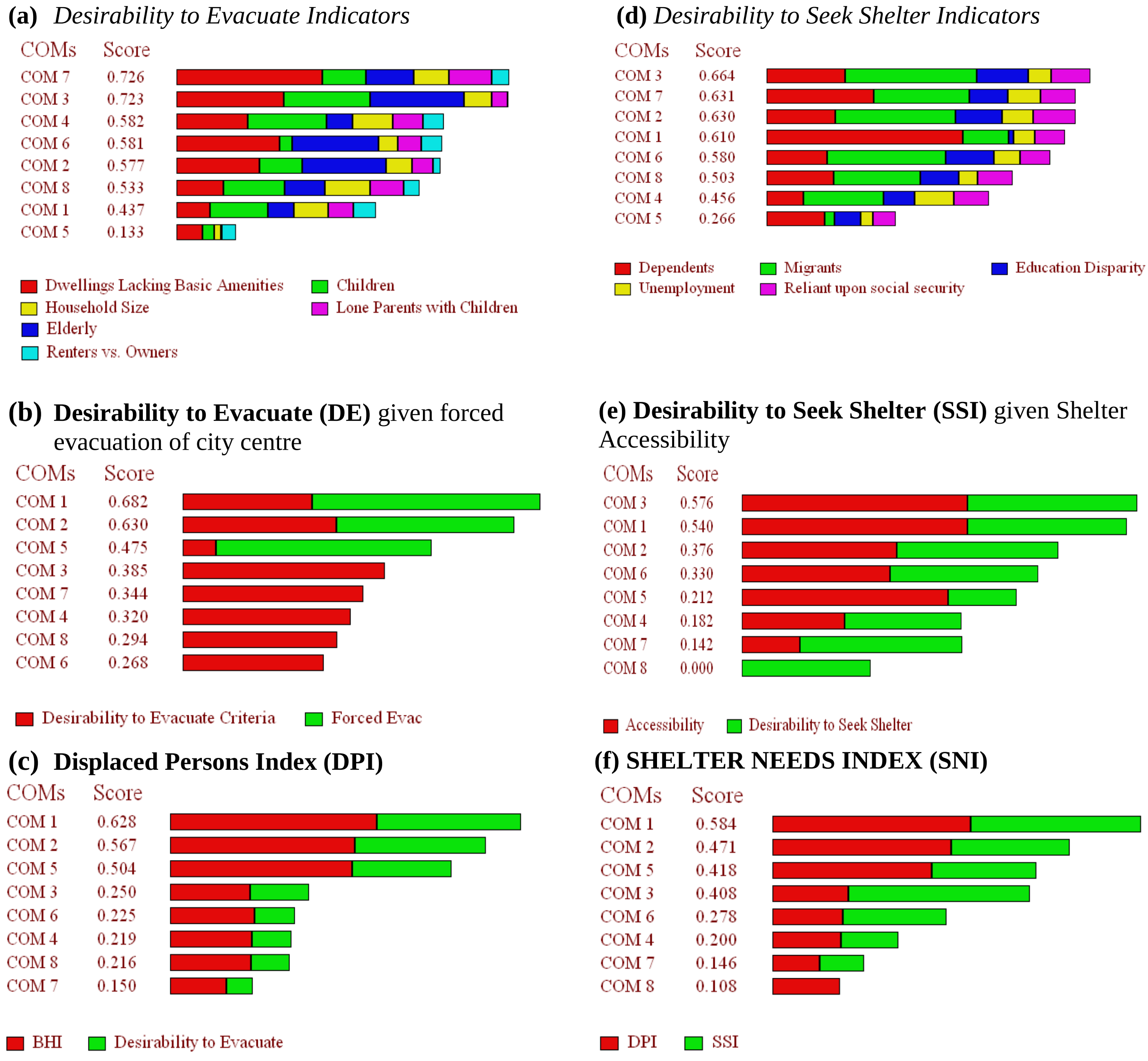

Figure 6 Ranking of the Displaced Persons (left, 6a-c) based on the Building Habitability Index (BHI) and the Desirability to Evacuate Criteria. Ranking of the Shelter Needs Index (right, 6d-f) based on the Desirability to Seek Shelter (SSI) Criteria and the Displaced Persons Index.

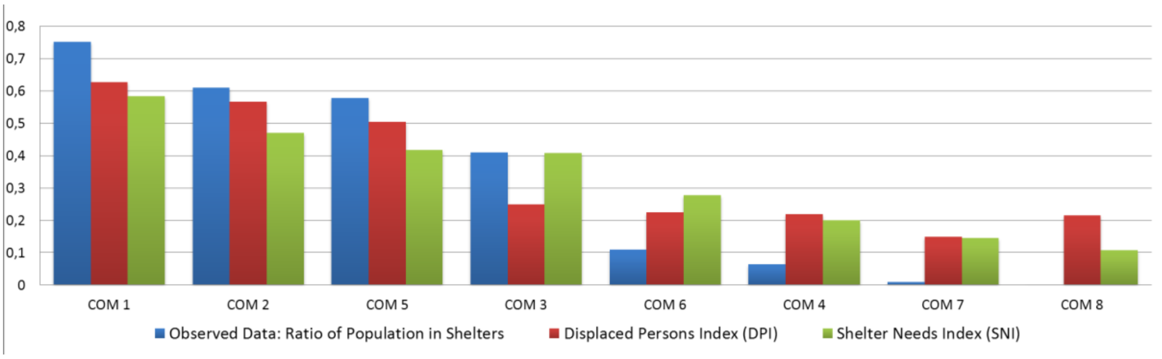

Figure 7 Ratio of actual population in shelters (Observed data) shown against the ranking of displaced persons and shelter needs in the 8 COMs.

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