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SOFTWARE FOR MEASURING DISASTER COMMUNITY RESILIENCE ACCORDING TO THE PEOPLES METHODOLOGY

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Abstract.

Resilience is defined as the ability to mitigate hazards disposing a prompt strategy for recovering activities. Many papers are available in literature describing community resilience performances, but very few describe how to quantitative measure this index and which tools to use. The paper presents a software for evaluating community resilience index using the PEOPLES framework methodology. A critical comparison with similar softwares already available in literature is given emphasizing strengths and weakness with respect to the new proposed software, that has a user friendly graphical interface in Google earth environment. Finally the program and the methodology are tested using the case study of the 2009 Italian earthquake in L'Aquila that mainly affected historical monumental buildings in downtown L'Aquila. Four different scenario events are assumed to describe the reconstruction phase (recovery) and compared using the proposed platform.

1 INTRODUCTION

In recent years, we have seen how important is planning after disasters (e.g., L'Aquila and Haiti earthquake, Hurricane Katrina, September 11th terrorist attack, etc.), so the concept of resilience, that is the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters, and carry out recovery activities in ways that minimize social disruption, has gained attention recognizing the fact that not all threats or disasters can be averted.

The community planning is affected by physical, social, and economic components of urban or rural communities. The main goal of this research is to develop tools that allow communities to reduce vulnerabilities while enhancing their overall resilience against extreme events and enabling sustainable development. When considering small communities such as rural communities, their residents are faced with multiple conflicting decisions when responding to natural and man-made hazards. Hazard mitigation practices of rural communities include best management practices in soil and water conservation to reduce soil erosion and flooding.

Resilience has been defined as a measure of geospatial and temporal functionality, its decay and recovery, in face of various hazards [1]. The functionality and resilience of a community depend on numerous components and dimensions. In previous research [2][3], seven dimensions of community resilience were identified and represented in the holistic, interdisciplinary framework with the acronym PEOPLES: *Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital*. The PEOPLES Resilience Framework provides the basis for development of quantitative and qualitative models that measure the resilience of communities against extreme events in any or a combination of the above-mentioned dimensions, using risk assessment, loss estimation and recovery tools. The methodology has been implemented in software and the first release of it is presented for the first time in this paper. In the current version only the physical and infrastructure dimension has been developed, while other resilience dimensions have been set up in the graphical user interface waiting for approval from the scientific team of the PEOPLES framework developers. A case study of an Italian region recently affected by an earthquake has been used to prove the applicability of the developed software.

2 CRITICAL REVIEW OF CURRENT RESEARCHES

Several methods are available in literature for loss estimation methodologies. Among all the most famous is HAZUS [4], a software that was developed by the National Institute of Building Sciences (NIBS). The model uses and works on inventory of the classification of various components like population, building, transport system, lifeline utilities and hazardous materials. The building inventory is made for groups of buildings, with similar characteristic. The buildings are divided by groups of pre-defined building classes. There are 36 different *structural classes* that depend by construction, material, and structural type, while the *occupancy inventory* of the general building stock in the HAZUS methodology is prepared on the basis of its general and specific building occupancy. The building and occupancy type inventory are used, respectively, for the building risk assessment and to evaluate the potential economic losses. It is important to mention that this methodology evaluates only building risk assessment without any evaluation of the recovery plan and only a gross estimation of the recovery time.

More recently another software has been developed called *ResilUS* that is a prototype simulation model for community resilience to disasters [5][6][7]. ResilUS uses a macro-subdivision of area, like the neighborhoods subdivision, where are contained within a broader community. The model represents damage and recovery associated with a hazard event into three elements of community capital (economic, technological and human or, for businesses, individual), which is limited to buildings and lifelines (transportation network, electrical network, water network and critical facilities). ResilUS relies on two generic indicators of resilience that are the ability to perform and opportunity to perform associated with each hierarchical scale (community, neighbourhood, agent). Resilience, of agents, infrastructure, or communities, is measured in terms of some indicator of performance (e.g. level of service, building stock, income, or gross regional product). The model has four recovery curves, but currently the software *ResilUS* uses only one curve, that brings back to pre-disaster conditions.

In Europe another software package has been developed that is called *SELENA–RISe* open risk package [8][9], which was developed by the international centre for geohazards (ICG), through NORSAR (Norway) and the University of Alicante (Spain). It consists of the two separate software tools SELENA (Seismic Loss Estimation using a Logic Tree Approach) and RISe (Risk Illustrator for SELENA). SELENA is the computational platform that evaluates the building risk and potential losses (economic and casualties), while RISe converts the output files of SELENA, in order to plot on Google Earth. The software uses the HAZUS methodology to evaluate damage of the general building stock and the economic and human losses related to these physical damages. SELENA uses different building codes and models (e.g. EC8 [10], IBC-2006 [11], IS 1893 [12], CSM [13] [14], etc. The limitation of the software consists in extensive data input requirements, without a user friendly graphical interface, because it has two separate softwares, both running in MATLAB environment.

Based on the above observation there is need for a new software that takes in account the time dimension of the disaster and the entire recovery process.

3 PEOPLES FRAMEWORK

Disaster resilience is often analyzed considering technological and social units, but also considering the spatial scale of analysis, (e.g. single buildings, towns, communities, regions, country etc.). Technological aspects mainly focus on performances and interdependencies of different networks and systems. The human component is also central, because resilience depends first on the actions of people operating at the individual and neighborhood scale. Community resilience also depends heavily on the actions of different levels of government and its agencies at the local and regional scales when a disruptive extreme event occurs.

The PEOPLES Resilience Framework is built on, and expands, previous research at MCEER linking several previously identified resilience dimensions (i.e., technical, organizational, societal, and economic) and resilience properties (i.e., R^4: robustness, redundancy, resourcefulness, and rapidity) [15][16][17]. In detail, the methodology subdivides the community resilience in seven dimensions, which are listed below:

- **P** opulation and Demographics (Composition, Distribution, Socio-Economic status, etc.);
- **E** nvironmental/Ecosystem (Air quality, Soil, Biomass, Biodiversity, etc.);
- **O**rganized Governmental Services (Legal and security services, Health services, etc.);
- **P** hysical Infrastructure (Facilities, Lifeline, etc.);

- **L** ifestyle and Community Competence (Quality of Life, etc.);
- **E** conomic Development (Financial, Production, Employment distribution, etc.);
- **S** ocial-Cultural Capital (Education services, Child and elderly care services, etc.).

All dimensions are measured by functionality indices that measure the performances, so the PEOPLES Resilience Framework defines components of functionality using a geospatial-temporal distribution within its geographical influence boundaries. Interdependencies between and among these components are key to determining the resilience of communities (recovery plan). The resilience can be considered as a dynamic quantity that changes over time and across space. The PEOPLES Resilience Framework requires the combination of qualitative and quantitative data sources at various temporal and spatial scales, and as a consequence, information needs to be aggregated or disaggregated to match the scales of the resilience model and the scales of interest for the model output.

4 SOFTWARE DESCRIPTION

A software that uses the methodology of PEOPLES Resilience Framework (ArciRasilience1.0) to measure the Resilience index at the Community Scale was created.

Firstly, our interest was focused in "Physical Infrastructure" dimension, in particular in building structures, like Facilities or Health Care. The software is divided in five parts:

1. *Input data collection (e.g. building network characteristics, etc.);*
2. *Damage State Probability Analysis;*
3. *Resilience analysis;*
4. *Output data;*
5. *Decision making;*

4.1 Input data collection

Data input of physical infrastructures will be collected in a database in a central server through the access to the website of the project (www.polito.it/ICRED). The access to submit the input data from users will be controlled by a username account with password. The input data required by the program are the following:

- *Infrastructure Localization and Geometry parameters;*
- *Physical Infrastructure parameters;*
- *Damage parameters (e.g. capacity curve, damping ratio, occupancy class, construction building times, functionality losses, etc.);*

While, the services data, that are available inside the software, are the parameters that define the seismic action according to Italian Seismic Standard [18] (PGA, F_0 and T^*_c) and some parts of HAZUS database [4].

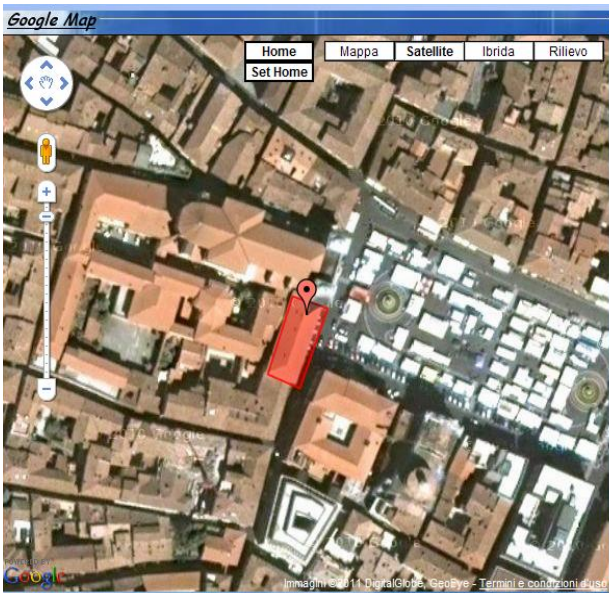

Figure 4-1: Data input interface for Localization and Geometry of Infrastructure.

Figure 4-1 shows how the geometry of the infrastructure is drawn using the Google Maps interface, while the physical infrastructure characteristics are defined using the classification given in the PEOPLES Resilience Framework [1] that will be used to evaluate the corresponding fragility curves as shown in Figure 4-2.

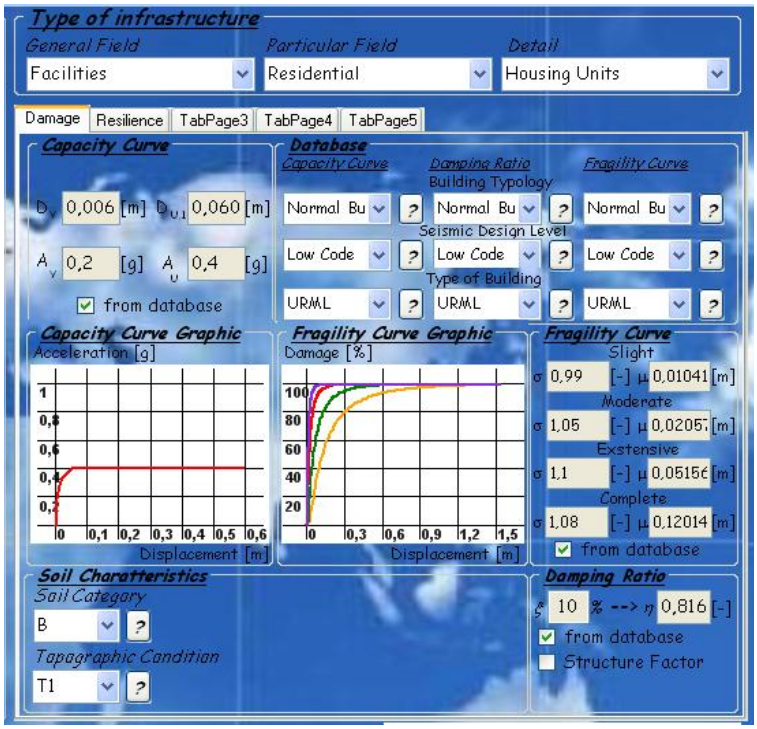

Figure 4-2: Data input interface for Damage features.

The building response is evaluated using the capacity spectrum method (CSM) rather than nonlinear time history analysis, because it is faster when several building performances need to be evaluated in a given region. When evaluating seismic response the software uses the capacity curves provided by HAZUS database [4], but they can also be assigned directly from

the users. Seismic demand is evaluated using the information provided in the Italian seismic standard, given the soil category and the topographic characteristics of the site. In the near future also the seismic demand according to the US seismic standard will be provided.
Another parameter assigned as input to evaluate the seismic response of the buildings is the damping ratio that can be assigned manually or using the default values recommended by HAZUS database [4]. The over strength factor (q) can also be assigned manually or directly evaluated according to the Italian seismic standard [18]. Also fragility curves associated to a given building typology are evaluated using the HAZUS database or assigned manually from the user. Other parameters necessary to evaluate resilience are the occupancy class, the total occupancy area, the full replacement costs, the construction building times, the recovery costs and the functionality losses (Figure 4-3).

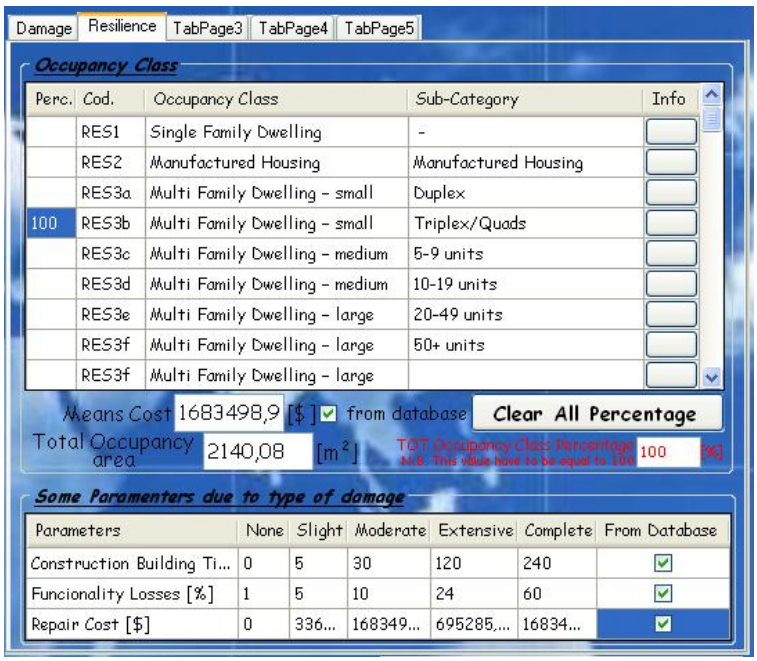

Figure 4-3: Data input interface for Resilience features.

The general building stock is also classified according to the occupancy class of HAZUS, but it is divided into general occupancy and specific occupancy classes. The general occupancy classification system consists of seven groups (*residential, commercial, industrial, religion/nonprofit, government, education and lifelines*). There are 33 specific occupancy classes. While the total occupancy area is the sum of the all occupancy areas used by the respective occupancy classes presented inside the building.

Another feature is the building time for each damage state that is defined as the sum of the time spent for building cleanup and repair. If using the HAZUS database [4] these values are function of occupancy classes inside the building. The recovery costs, instead, are defined as the building repair costs due to each damage state (slight, moderate, extensive and complete). In HAZUS these values are function of full replacement cost and of the occupancy classes inside the building. Finally, the functionality losses are the percentages of the building functionality loss at a given damage state (e.g. 1% none; 5% slight; 10% moderate; 24% extensive; 60% complete). If using the internal database these values depend on the occupancy classes inside the building.

4.2 Damage State Probability Analysis

The disaster induces a different damage state for each building. The problem is to predict how the damages will be distributed in the control area. The software provides the damage state due to earthquakes, in the buildings presented in the control area. The damage state probability for each building is calculated using the following steps:

- *Evaluate the response spectrum of the building;*
- *Calculate the peak displacement response of the building;*
- *Evaluate the damage states probabilities (slight, moderate, extensive and complete) of the building;*
- *Calculate the construction building time, repair cost and the functionality of the building after disaster.*

The response spectrum of the building is evaluated according to the Italian Seismic Standard [18] in the centroid of the building perimeter. In the next version of software, it will be possible using Ambraseys AR. To evaluate the peak displacement response of the building, the software takes the data obtained from the response spectrum (function of PGA and period of the structure) and transforms them to obtain a curve function of the pseudo spectral acceleration and the pseudo spectral displacement. The peak displacement response is defined as the abscissa of intersection point between the demand spectrum curve and the capacity curve of the building.

The damage states probability (slight, moderate, extensive and complete) are the values obtained from the four fragility curves of the building substituting the peak displacement response as parameter (see Figure 4-4).

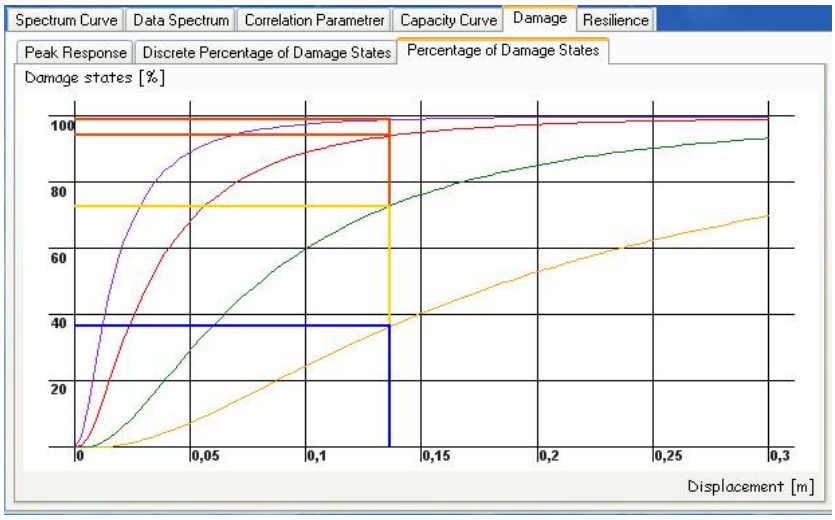

Figure 4-4: The probabilities of damage states.

The last step of damage state probability analysis is to evaluate the construction building time (which is the time spends on building cleanup and repair), the repair cost and the functionality of the building after the disaster. For the first two parameters (K_{TOT}), the software will use the same procedure of HAZUS, which consists in a summation of products between damage state probability (PDS_i) and the relative parameter (k_i) (construction buildings times or repair costs)(see Equation 1).

$$K_{TOT} = \sum_{i=1}^{4} PDS_i \cdot k_i \tag{1}$$

While for the building functionality, before the software evaluates the discrete probabilities of damage states ($DPDS_i$) (see Equation 2 and Figure 4-5) and after it uses the previous procedure (Equation 2) replacing the damage state probability with the discrete probability.

$$\begin{cases} DPDS_i = 1 - PDS_{i+1} & i = 0 \\ DPDS_i = PDS_i - PDS_{i+1} & i = 1,2,3 \\ DPDS_i = PDS_i & i = 4 \end{cases} \tag{2}$$

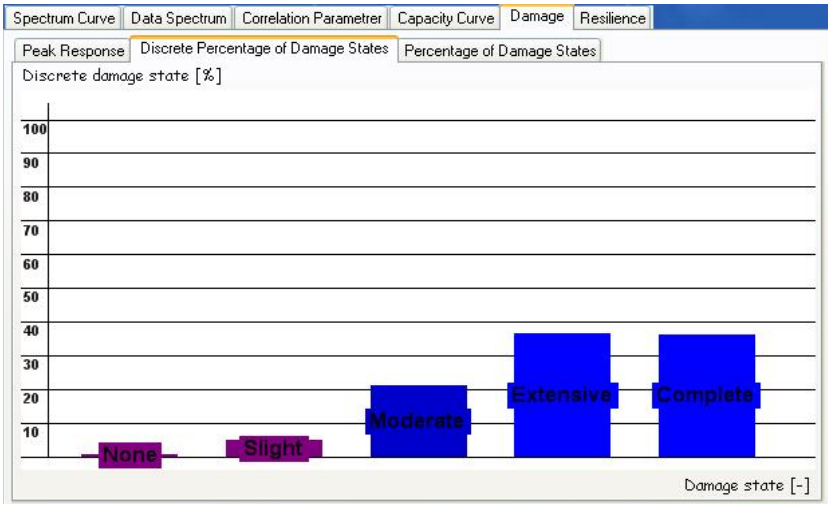

Figure 4-5: The discrete probabilities of damage states.

4.3 Resilience analysis

Resilience of the building (R_i) is defined as a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline networks, or community, over a control period T_{LC} ([T_A; T_B]), that is chosen by user. This quantity is defined graphically as the normalized area underneath the functionality function $Q_i(t)$ of the building (internally integrated with a discrete Simpson integral) and is defined analytically as follows:

$$R_i = \frac{\int_{T_A}^{T_B} Q_i(T)dt}{T_B - T_A} \tag{3}$$

Where the functionality $Q_i(t)$ ranges from 0 to 100% (where 100% mean no reduction in performance, while 0% means total loss).

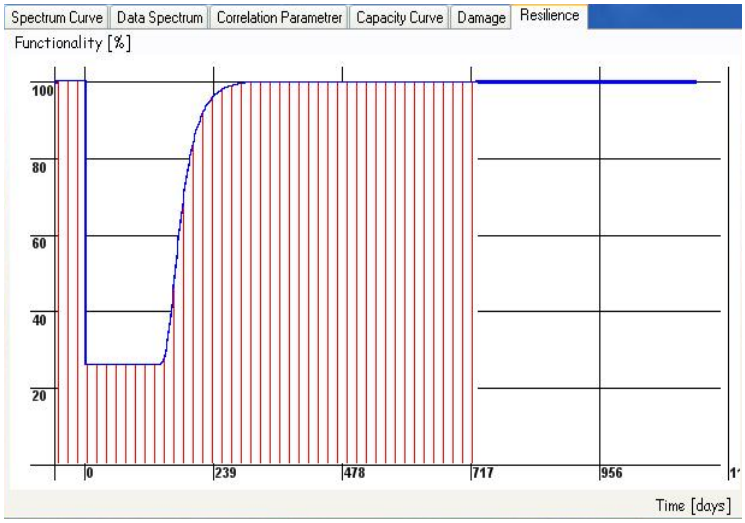

Figure 4-6: An example of recovery function.

The functionality function $Q_i(t)$ of the building is a function composed by two parts. The first part is constant, while the second one is lognormal (see Figure 4-6). The function is analytically defined as follows:

$$\begin{aligned} &Q_i(T) = 1 && T < T_{Dis} \\ &Q_i(T) = F_s && T_{Dis} \le T < T_{Ad} \\ &Q_i(T) = F_s + (1 - F_s) \cdot \Phi\left(\frac{\ln(T) - \mu}{\sigma}\right) && T_{Ad} \le T \end{aligned} \tag{4}$$

Where F_s = is the functionality of the building after disaster; Φ= is the lognormal function; σ and μ, are respectively the standard deviation and average value of the lognormal distribution; T_{Ad} and T_{Dis}, are the administrative and disaster times.

The length of the constant function is equal to the administrative time (that will be discussed in the following paragraph). While, the two coefficients of the lognormal function depend essentially from the type of infrastructure (for the μ value), the K value (ratio between construction building time CBT and average time μ) and the functionality value after building time (for σ value; see Equation 5).

$$\sigma = A \cdot \ln(K) = 0.384 \cdot \ln\left(\frac{CBT}{\mu}\right) \tag{5}$$

In finally, the resilience at the community scale of selected area (called community resilience R_C) is evaluated by a weighted average of all buildings resilience R_i, analytically defined as follows:

$$R_C = \frac{\sum_i R_i \cdot W_i}{\sum_i W_i} \tag{4-7}$$

where, the weight coefficients W_i depend by the type of infrastructure.

4.4 Decision making

The software can be used as decision making tools for communities to evaluate the effect of different recovery plans in terms of resilience. The software tests each possible combination of recovery processes (in agreement to the maximum possible number of simultaneous building sites in the selected area and the economic availability of the community) modifying the administrative times of each building (the administrative time is the time elapsed from the disaster to the start of repair works of the building). The software identifies as the better solution the one that has the major recovery velocity in each point of the functionality function (the recovery velocity is expressed as the value of the derivate of the functionality function). It also evaluates resilience and functionality of the buildings and the community (see Figure 4-7).

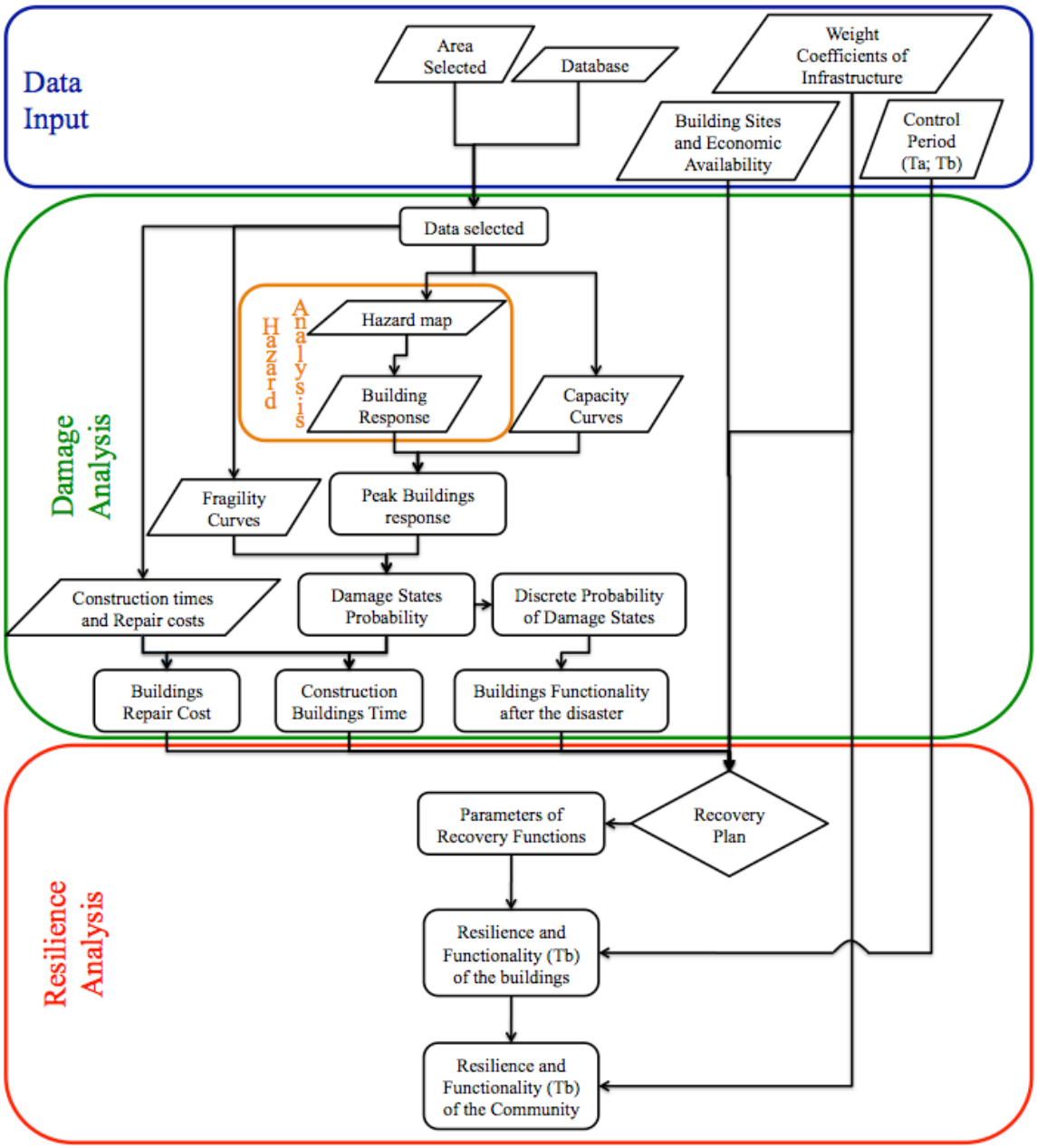

Figure 4-7: Flowchart of all steps to follow to evaluate the global resilience.

5 CASE STUDY

The software has been tested using as case study 10 buildings inside l'Aquila downtown (see Figure 5-8).

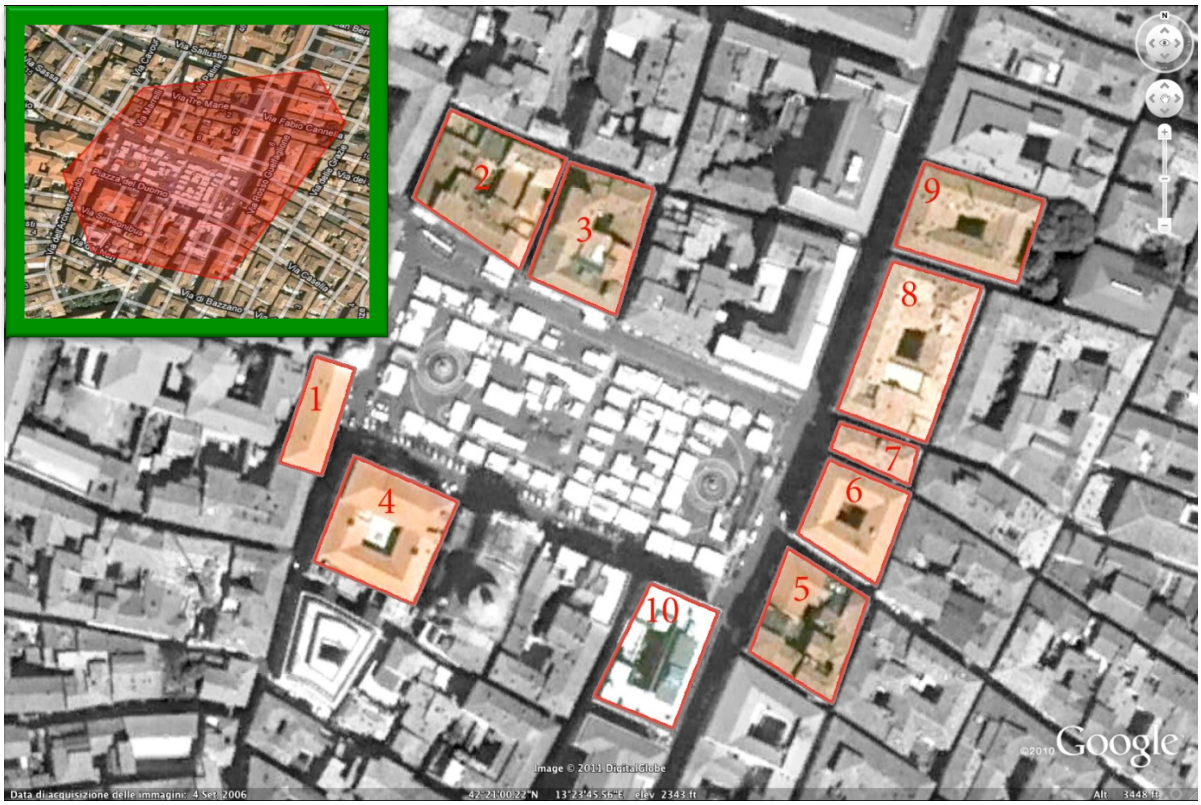

Figure 5-8: The ten buildings selected inside the city center of L'Aquila and in the high left corner there is the software interface for selected area.

The ten buildings selected have the follow features (Table 5-1; Table 5-2 and Table 5-3):

	NAME	TYPE OF INFRASTRUCTURE		
N°	Name	PEOPLES Classification		
1	Building 1	Facilities	Residential	Housing Units
2	Building 2			
3	Building 3			
4	Building 4		Commercial	Office Buildings
5	Building 5			
6	Building 6			
7	Building 7		Residential	Housing Units
8	Building 8			
9	Building 9		Commercial	Hotels - Accommodations
10	Building 10		Residential	Housing Units

Table 5-1: Data input for Localization and Type of Infrastructure.

DAMAGE FEATURES

N°	Soil Category	Topographic Condition	Building typology	Seismic Design Level	Type of Building	Description	Stories
1	B	T1	Normal Building	Low code	URMM	Unreinforced Masonry Bearing Walls	3
2					C1M	Concrete Moment Frame	4
3				High code	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	3
4			Special Building	Moderate code			2
5			Normal Building				3
6							
7					C1M	Concrete Moment Frame	4
8					RM2M	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	
9			Special Building	Low code	URMM	Unreinforced Masonry Bearing Walls	
10			Normal Building	High code	C2M	Concrete Shear Walls	

Table 5-2: Data input for Damage features.

RESILIENCE FEATURES

N°	Occupancy Class	Description	Sub-category	Total Occupancy Area [m^2]
1	100% RES3b	Multi Family Dwelling – small	Triplex/Quads	2.140,08
2				6.641,45
3	67% RES3a 33% COM1	Multi Family Dwelling – small Retail Trade	Duplex Dept Store, 1 st	4.952,12
4	100% COM4	Prof./Tech./Business Services	Office, Small	3.841,74
5				4.392,80
6				2.702,28
7	75% RES3a 25% COM1	Multi Family Dwelling – small Retail Trade	Duplex Dept Store, 1 st	1.213,80
8	100% RES3b	Multi Family Dwelling – small	Triplex/Quads	6.628,45
9	100% RES4	Temp. Lodging	Hotel, medium	4.850,70
10	100% RES3b	Multi Family Dwelling – small	Triplex/Quads	4.719,35

Table 5-3: Data input for Resilience features.

The test evaluates four different recovery plans having the same limit state characteristics but different site availability - i.e. number of construction sites that might fall within the considered area.

The first and fourth scenarios have, respectively, the maximum and minimum availability, that consists having respectively a maximum of 10 and 0 building construction sites per day inside the selected area (there is not limitation for simultaneous start of construction sites). The second scenario has the maximum limit of five construction building sites per day and of four simultaneous starts of construction building sites. While, the third scenario has the limit of one building site per day (no-limit for simultaneous starts of building sites). In all cases there is no-limit on economic budget. It was found the following results that are summarized in the tables below assuming a return period for the earthquake of 2475 years and a control period of 2 years.

GLOBAL RESILIENCE OUTPUT DATA

Case:	I	II	III	IV
Community Resilience (Ta; Tb) [%]:	98,3	95,0	74,8	58,2
Community Functionality (Tb) [%]:	100,0	100,0	88,6	58,2

Table 5-4: Output data of Global Resilience for each case.

DAMAGE OUTPUT DATA FOR EACH BUILDING

Building N°	S_d [m]	S_a [g]	PDS-s	PDS-m	PDS-e	PDS-c	DPDS-n	DPDS-s	DPDS-m	DPDS-e	DPDS-c	CBT [days]	SF [%]	RC [$]
1	0,222	0,136	99	94	73	36	1	5	21	37	36	138	45,2	905294
2	0,156	0,242	100	97	71	32	0	3	26	38	32	131	48,1	2651047
3	0,745	0,041	84	55	14	2	16	29	41	12	2	31	84,9	418350
4	0,627	0,048	83	60	19	3	17	24	40	16	3	40	82,5	595000
5	0,506	0,060	90	75	36	7	10	16	38	30	7	64	74,3	1108495
6	0,506	0,060	90	75	36	7	10	16	38	30	7	64	74,3	681906
7	0,300	0,126	96	82	31	7	4	13	51	24	7	59	74,1	201859
8	0,421	0,090	91	75	27	4	9	16	48	22	4	53	77,8	983131
9	0,333	0,091	97	84	46	12	3	13	38	33	12	82	67,4	1653549
10	0,548	0,069	87	45	4	0	13	42	41	4	0	19	89,2	242968

Table 5-5: Output Damage data for each building.

Table Legend:
N°: Infrastructure number [-];
S_d: Peak displacement response [m];
S_a: Peak acceleration response [g];
PDS-: Probabilities of damage state (s: slight, m: moderate, e: extensive and c: complete) [%];
DPDS-: Discrete probabilities of damage state (n: none, s: slight, m: moderate, e: extensive and c: complete) [%];
CBT: Construction building time [days];
SF: Start functionality value [%];
RC: Recovery cost [$].

Figure 5-9: Histogram of discrete probability of damage states.

From the Table 5-5 and Figure 5-9 it is possible to see how are distributed the damage states in all buildings presented in the selected area. The buildings that have the higher damages are the buildings 1, 2 and 9. This result was easy to predict because the three buildings are designed with low seismic design level (low code). Instead Figure 5-10 shows the contour plot of functionality immediately after the disaster. In this case, the lower values of functionality are near buildings 1 and 2 in the plot, because the functionality is diffused through the weighted average.

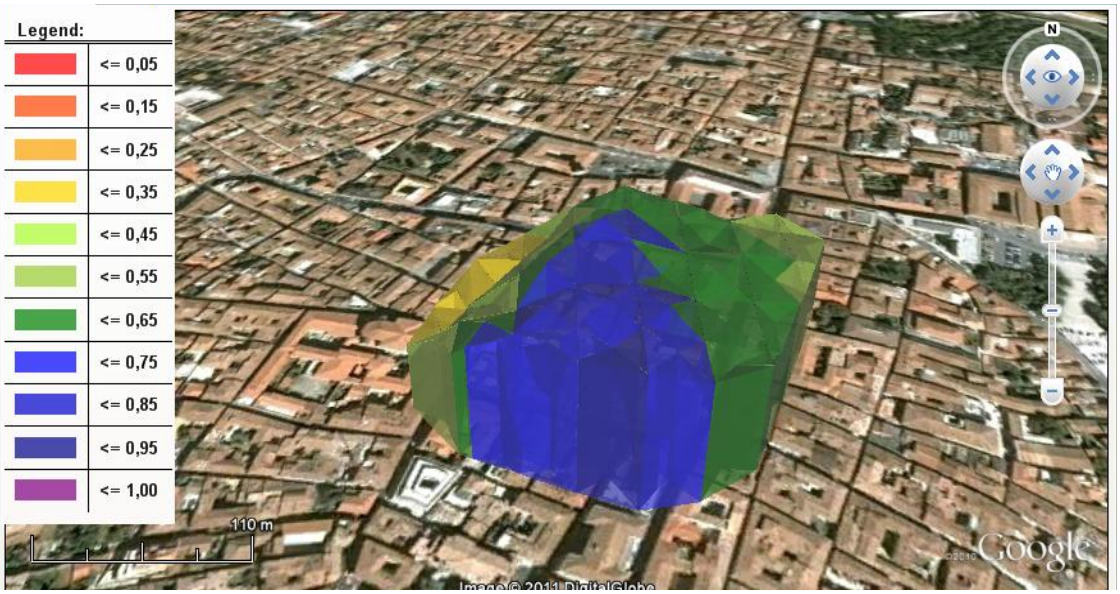

Figure 5-10: Contour plot of functionality.

RESILIENCE OUTPUT DATA FOR EACH BUILDING

Case:	I	II	III	IV	I	II	III	IV
Building N°	AT [days]				RES [%]			
1	0	133	152	inf.	95,6	82,1	80,2	45,2
2	0	91	336	inf.	96,0	87,2	63,8	48,1
3	0	0	0	inf.	99,6	99,6	99,6	84,9
4	0	0	51	inf.	99,4	99,4	97,5	82,5
5	0	34	843	inf.	98,7	96,9	61,3	74,3
6	0	51	744	inf.	98,7	96,0	61,3	74,3
7	0	34	643	inf.	98,6	96,6	61,7	74,1
8	0	0	942	inf.	98,9	98,9	64,3	77,8
9	0	66	511	inf.	97,7	93,0	61,4	67,4
10	0	0	118	inf.	99,8	99,8	97,2	89,2

Table 5-6: Output data of Resilience features for each building and each case.

Table Legend:
AT: Administrative time [days];
RES: Resilience over the control period [%].

Table 5-6 shows the administrative time, the resilience over the control period and the rank in recovery plan for each building.

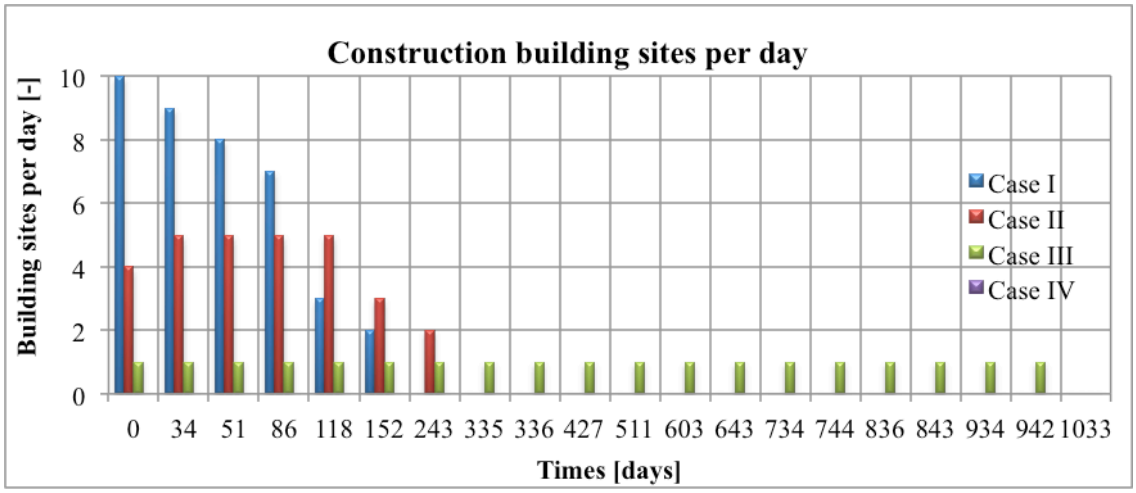

Figure 5-11: The number of building sites per day for each case.

As mentioned above, the only difference between various cases is the buildings sites availability (men / day), which is shown on Figure 5-11. Case I requests immediately an higher number men per day, while cases III, IV and II (more realistic and efficient) have a constant or homogeneous distribution in the time.

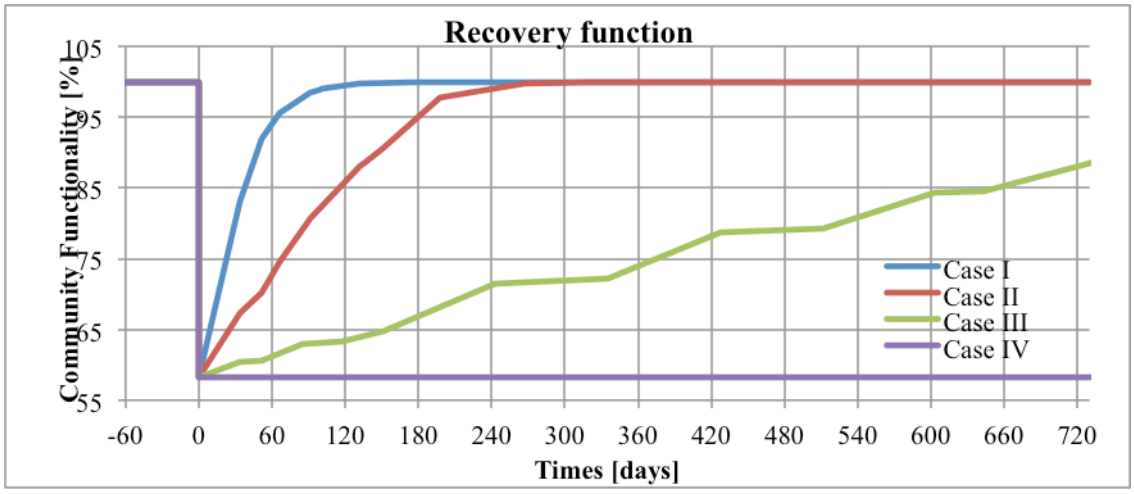

Figure 5-12: Recovery function for each case

From the Figure 5-12, that shows the four functionality functions for each case, it is possible to observe that the case I is the most resilient, while the case IV has the smallest values of resilience. The case III is like a cumulative sum of all functionality functions of the buildings, because the works follow each other sequentially.

RESILIENCE INDEX

Case:	I	II	III	IV
Community Resilience index [%]:	92,0	87,6	80,6	58,2
Time of completion of work, T_{CW} [days]:	183,9	316,8	1033,0	inf.

Table 5-7: Output data of Global Resilience for each case.

The resilience index in Table 5-7 is defined as the value of community resilience from the disaster time T_{Dis} to the time of completion of the works T_{CW} (at this time the functionality will be equal to 100% or highest value). This index decreases with decreasing of the velocity of recovery, so it is a good parameter to evaluate the performance of the community and of the chosen recovery plan.

6 CONCLUSIONS

This paper presents a software able to evaluate the disaster resilience of communities and systems in general using the PEOPLES framework methodology. The main advantage with respect to the other software already available is the simple graphical interface that uses the Google earth visualization. This platform can be used both for data input, but also for output visualization. The output file are available both in a excel format and in a KML file readable by Google Earth.

The PEOPLES framework developed in the software integrates the information from different fields in a unique function that reach results that are unbiased by uninformed intuitions or preconceived notions of how large or how small the risk is.

Finally the program and the methodology are tested using the case study of the 2009 Italian earthquake in L'Aquila. Four different scenario events are assumed to describe the reconstruction phase (recovery) and compared using the proposed platform.

Some assumptions that are made for one case can not be so important for others, so engineers and decision makers during the calculation of the community resilience index should focus on the assumptions that most influence the problem at hand.

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