Disaster Resilience Assessment of Building and Transportation System

DISASTER RESILIENCE ASSESSMENT OF BUILDING AND TRANSPORTATION SYSTEM

G.P. Cimellaro[1], V. Arcidiacono[2], A.M. Reinhorn[3]

ABSTRACT

The paper presents a new methodology to assist decision-makers in the management of critical events such as earthquakes evaluating the recovery time, and the resilience index of a building system that is a component of the physical infrastructure dimension of the PEOPLES Resilience framework. The interdependencies between building system and transportation network in term of accessibility is modelled. Finally, the methodology has been implemented in a software and has been applied in two case studies: *a*) the old medieval centre of L'Aquila town and *b*) the Treasure Island in the San Francisco Bay area.

Keywords: *Community resilience, disaster resilience, infrastructure interdependency, PEOPLES framework, restoration process, recovery, loss estimation, seismic hazard.*

1 INTRODUCTION

The tendency to globalize services, the ever-growing population, and the trend to push social, economic, technological, and biological systems to their limits are all likely to increase the frequency of large-scale disasters [Allan, 2013]. For example, electrical power outages ("blackouts") have affected larger and larger areas. This is because of the growing and considerably varying demand of electricity (e.g. due to a greater number of air conditioners), the greater size and complexity of electrical power networks (often with a power exchange across countries), and the de-regulation of the power market (which encourages profits with minimum investments).

Interconnected causality chains, i.e. a damage in a sector of a system affects the other systems, can describe the spreading of natural and man-made disasters. It is often these cascade effects (i.e. chain-reactions) by which a localized event in time and space causes a large-scale disaster, which

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may affect the whole community [Helbing et al., 2006]. Therefore, redundancies are required to stop the chain-reactions, and for adapting to the changes of the economical and environmental conditions. For example, the earthquake in Kobe (Japan, 1995), was very destructive for both the towns and the highways. The main problems were the several fires, which were caused by broken gas pipes in wooden houses between skyscrapers. A great chaos was caused by the fact that the fire fighters could not reach the fires, because of the damage to the critical infrastructures (lifelines) such as the road network and to the water distribution network with many broken and/or dysfunctional water pipes. Thousands of people were homeless and panicked during the aftershocks. In addition, the power supply lines, hanging over the remaining streets, obstructed seriously the traffic, the transportation and the power supply. Hence, awareness of both manmade and natural disasters has increased in recent years and the concept of resilience has gained attention, because small damages can become catastrophes when the communities have no access to the emergency services [Arcidiacono and Cimellaro, 2013; Cimellaro et al., 2013; Scura et al., 2013].

Therefore, the paper is focusing on the vulnerability of the transportation system and its use in emergencies using a methodology – which is based on the PEOPLES framework [Renschler et al., 2010, Cimellaro et al., 2016] – that is able to assess the resilience index of the physical infrastructure dimension during an extreme event. In detail, the paper focuses on the Building System [Arcidiacono et al., 2011] and its interdependencies with the Transportation System [Arcidiacono et al., 2012a; 2012b]. In particular it models functionality and resilience of this type of infrastructure.

2 STATE-OF-ART OF CURRENT METHODOLOGIES

The definition of Resilience adopted in this paper is “the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters, plan and enact an effective strategy to recover its activities so as to minimize social disruption” [Bruneau et al., 2003; 2007].

Moreover, the methodology was implemented in a software [Arcidiacono et al., 2011; 2012a; 2012b; Cimellaro et al., 2013], which is able to assist decision-makers to prevent and minimize the disasters effect.

Several methods are available in literature for loss estimation methodologies. Among them, the most famous is the HAZUS (abbreviation for **Haz***ards* **U***nited* **S***tates*) framework [Whitman et al., 1997; FEMA, 2003; 2005] which was developed by the National Institute of Building Sciences (NIBS) and used by FEMA in 1997 to assess separately earthquake, wind, and flood losses within the USA. The method works on an inventory of various components such as population, buildings, transportation systems, lifeline utilities, and hazardous materials. It evaluates the status of a community – according to the direct and indirect losses due to social, economic, and physical aspects – with a multi-risk analysis approach. The losses are provided in probabilistic terms evaluating causalities, shelters, inundations, fires, debris, hazardous material releases, damage states of physical infrastructures, and economic losses. Buildings are grouped in building classes with similar characteristics making a building inventory. There are 36 different structural classes that depend on the construction type, the material, and the structural type, while the occupancy inventory of the general building stock in the HAZUS methodology is prepared based on 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. HAZUS methodology considers all hazards, but not all the interdependences between the structural components. For example, the damage of the transportation network inducted by the building debris is not modelled. Therefore, the methodology is "limited" to the risk assessment – not considering the functionality and the recovery plan – making it a useful tool to prevent damages and to design urban cities, but not to manage the communities during the catastrophic events.

More recently, the ResilUS framework [Miles and Chang, 2006; 2007; 2011], based on the resilience concept, has been developed. It is limited to buildings and lifelines (transportation network, electrical network, water supply, and critical facilities) and uses a macro-sub division of area contained within a broader community such as the neighbourhood subdivision, and subdivides the community in three elements that are: the physical built environment, economics, and humans (i.e., health). The method relies on two generic indicators of resilience: (i) the *ability* to perform and (ii) the *opportunity* to perform. These recovery indicators are specifically represented by multiple variables. For example, the indicator of the ability to perform for households is represented by the household health, while the reconstruction time is influenced by the size (single-family vs. multi-family) of the respective building in addition to the construction capacity in the community (opportunity to perform). The model has four recovery curves, but currently the software ResilUS uses only one curve, that brings back to the pre-disaster conditions. The framework, therefore, facilitates the creation of a database for infrastructures and defines multiple resilience indicators making the optimal solution difficult to find, but different functionality models already available in the literature can be adopted.

3 PROPOSED METHODOLOGY

The methodology proposed in this paper is based on the PEOPLES Resilience framework [Cimellaro et al., 2016, Renschler et al., 2010]. In the method community resilience is evaluated combining seven dimensions – that are subdivided in components and sub-components – identified with the acronym P.E.O.P.L.E.S. (**P**opulation and demographics, **E**nvironmental/Ecosystem, **O**rganized governmental services, **P**hysical infrastructures, **L**ifestyle and community competence, **E**conomic development, and **S**ocial-cultural capital). The Resilience can be considered as a dynamic quantity that changes over time and across space. This is analytically defined as the normalized shaded area underneath the functionality performance function *Q(t)* of a generic system:

$$R\left(\vec{r}, t_{OE}, T_{LC}\right) = \int_{t_{OE}}^{t_{OE}+T_{LC}} \frac{Q_{TOT}\left(\vec{r}, t\right)}{T_{LC}} \cdot dt \tag{1}$$

where T_{LC} is the control time of the period of interest; t_{0E} is the time instant when the event happens; $\vec{r}$ is a vector defining the position within the selected region where the resilience index is evaluated [Cimellaro et al., 2010a], and $Q_{TOT}(\vec{r},t)$ is the global functionality of the region considered that is evaluated combining the performance indicators of each dimension of the resilience framework and is defined as follows [Reinhorn and Cimellaro, 2011]

$$Q_{TOT}(\vec{r},t) = Q_{TOT}(Q_P, Q_{Env}, Q_O, Q_{Ph}, Q_L, Q_{Eco}, Q_S) \tag{2}$$

where Q_x are the functionalities of the seven dimensions of the PEOPLES framework [Cimellaro et al., 2016]. The proposed methodology uses as key indicators the recovery time T_{EW}, the global functionality $Q_{TOT}(t)$, the resilience indicator $R(\vec{r}, t_{OE}, T_{LC})$ associated to each dimension and the community resilience index RI. The latter is defined as the resilience value R at the end of the recovery works T_{EW} (i.e. when the functionality reaches the expected value that can be greater or less than 100%) starting from the disaster time t_{OE} (i.e. when the disaster occurred).

$$RI(\vec{r}) = R(\vec{r}, t_{OE}, T_{EW}) \tag{3}$$

Once the community resilience index is defined, different scenarios of restoration plans can be considered, while the scenario that maximizes the Resilience index R and minimizes the recovery time, T_{EW} is selected.

4 PHYSICAL INFRASTRUCTURE DIMENSION

The term *infrastructure* has been used in English since 1887 and in French since at least 1875, originally meaning “The installations that form the basis for any operation or system” [Lewis, 2008]. The word is a combination of the latin word “infra”, meaning “below”, and “structure”. It can be defined as “the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance societal living conditions" [Fulmer, 2009]. The literature is characterized by the lack of an accepted description for infrastructure. The definition of infrastructure adopted in this paper includes highways, streets, roads, and bridges; mass transit; airports and airways; water supply and water resources; wastewater management; solid waste treatment and disposal; electric power generation and transmission; telecommunications; and hazardous waste management – and the combined system these modal elements comprise. However in the definition of infrastructure are also included the operating procedures, management practices and development policies that interact together with societal demand and the physical world.

The *physical infrastructures* correspond to a subcategory of infrastructures and refer to the basic physical structures required for an economy to function and survive, such as transportation networks, a power grid and sewerage and waste disposal systems.

The methodology proposed in this paper describes how to evaluate the functionality of the *Physical Infrastructure* dimension according to the PEOPLES framework, dividing it in 5 levels (Dimensions, Systems, Categories, Sub-categories, and Boundary levels) (Figure 1). The seven dimensions of the PEOPLES framework are included at the *Dimension level* in Figure 1 and because in the paper we are focusing on the *Physical Infrastructure dimension*, the latter is emphasized with respect to the other dimensions. Furthermore, the functionality of the *Physical Infrastructure* dimension $Q_{Ph}(t)$ is analytically defined as

$$Q_{Ph}\left(t\right)=\frac{\sum_{i} w_{s,i}^{Ph}\cdot Q_{s,i}^{Ph}\left(t\right)}{\sum_{i} w_{s,i}^{Ph}} \qquad (4)$$

where $Q_{s,i}{}^{Ph}(t)$ and $w_{s,i}{}^{Ph}$ correspond to the functionalities and the weight coefficients associated to the i-th system respectively. At the *System level,* for the same reason above, it is made distinction between "building system", described in more detail in paragraph 4 and "other systems". The *Categories level* evaluates the redundancy ratio of certain categories of elements that create a system, while the *Sub-categories level* calculates the functionality of each element of the infrastructure, evaluating dependencies and interdependencies between dimensions, systems, category, and sub-category. Finally, the *Boundary level* evaluates the damages and the recovery plan of the physical infrastructure units.

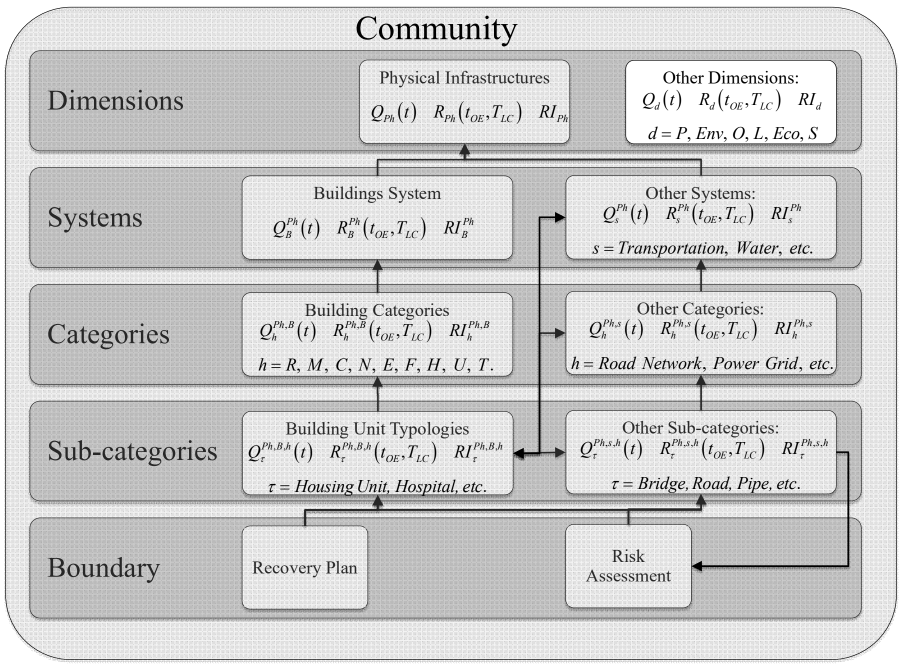


Figure 1. Flowchart for evaluating the Building System functionality and resilience according to the PEOPLES framework [Cimellaro et al., 2016].

5 BUILDINGS SYSTEM

The *Buildings System* is defined as a group of *building units* interconnected each other, which use and supply *services* from/to the community for any activity. The term *building unit*, i.e. construction, refers to "*a relatively permanent enclosed construction over a plot of land, having a roof and usually windows and often more than one level, used for any of a wide variety of activities, as living, entertaining, or manufacturing*" [dictionary.com, 2013]. While, the *building services* are "*the utilities, including electricity, gas, steam, telephone, and water, supplied to and used within a building*" [AAMI, 2013].

The proposed methodology identifies redundancies of building typologies and interdependences between and among building units and utilities, i.e. lifeline systems, as key factors, i.e. performances, of the buildings system. It means that the functionality of the building unit is related among all of dimensions, systems, categories, and sub-categories (Figure 1).

5.1 Redundancy

Redundancy is an attribute of resilience and it represents the duplication of available resources in a system with the intention of increasing its reliability. For example, the functionality of the *building category* – i.e. a class or group of building units that have some qualities in common, e.g. residential housing units, health care facilities, etc. – depends on its redundancy or in other words the number of units with similar characteristics. If we focus on health care facilities, a single hospital is less resilient with respect to an hospital network during an emergency, because the redundancy of this specific building category in a network is higher.

The proposed methodology has identified nine *classes* or *categories* within the *Building system* that have common features (Table 1). Then each *category* is divided in *sub-categories* that identify a typology of the building unit.

Table 1. Building System: Categories and Typologies.

System $\left(s : w_s^{Ph}\right)$	Categories $\left(h : w_h^{Ph,B}\right)$	Sub-categories $\left(\tau : w_\tau^{Ph,B,h} : U_{\tau,u}^{Ph,B,h} : W_{NS,u}^{Ph,B,h,\tau}\right)$	
	Building Categories	*Building Unit Typologies*	
Buildings System (B : 96)	Residential (R : 13)	Housing Units	(HU : 10 : 0.50 : 0.70)
		Shelters	(S : 2 : 0.50 : 0.20)
		Hotels - Accommodations	(HA : 5 : 0.50 : 0.60)
		others	(O : n.d. : n.d. : n.d.)
	Commercial (M : 9)	Distribution Facilities	(DF : 6 : 0.60 : n.d.)
		Hotels - Accommodations	(HA : 5 : 0.60 : 0.60)
		Manufacturing Facilities	(MF : 5 : 0.60 : n.d.)
		Office Buildings	(OB : 5 : 0.60 : n.d.)
		others	(O : n.d. : n.d. : n.d.)
	Cultural (C : 5)	Entertainment Venues	(EV : 2 : 0.65 : n.d.)
		Museums	(M : 5 : 0.65 : n.d.)
		Religious Institutions	(RI : 7 : 0.65 : n.d.)
		Schools	(S : 10 : 0.65 : n.d.)
		Sports/Recreation Venues	(R : 2 : 0.65 : n.d.)
		others	(O : n.d. : n.d. : n.d.)
	Communications (N : 6)	Internet Supplies	(I : 7 : 0.40 : n.d.)
		Phones Supplies	(T : 10 : 0.35 : n.d.)
		TV Supplies	(TV : 8 : 0.50 : n.d.)
		Radio Supplies	(R : 5 : 0.60 : n.d.)
		Postal Supplies	(P : 2 : 0.65 : n.d.)
		others	(O : n.d. : n.d. : n.d.)
	Health Care (H : 27)	Hospitals	(H : 10 : 0.35 : 0.80)
		Clinics	(C : 3 : 0.45 : 0.80)
		others	(O : n.d. : n.d. : n.d.)
	Food Supply (F : 13)	Mall	(C : 10 : 0.65 : 0.60)
		Markets	(M : 5 : 0.60 : 0.50)
		others	(O : n.d. : n.d. : n.d.)
	Emergency (E : 20)	Police stations	(P : 8 : 0.35 : 0.50)
		Fire stations	(F : 10 : 0.35 : 0.50)
		others	(O : n.d. : n.d. : n.d.)
	Utilities (U : 7)	Electrical Supplies	(E : 8 : 0.35 : n.d.)
		Fuel/Gas/Energy Supplies	(FGE : 10 : 0.35 : n.d.)
		Waste Supplies	(W : 2 : 0.60 : n.d.)
		Water Supplies	(H : 8 : 0.40 : n.d.)
		others	(O : n.d. : n.d. : n.d.)
	Transportation (T : 7)	Aviation Supplies	(A : 10 : 0.60 : n.d.)
		Bridges Supplies	(B : 3 : 0.35 : n.d.)
		Highways Supplies	(H : 2 : 0.45 : n.d.)
		Railways Supplies	(R : 5 : 0.50 : n.d.)
		Transit Supplies	(T : 2 : 0.65 : n.d.)
		Vehicles Supplies	(V : 1 : 0.65 : n.d.)
		Waterways Supplies	(W : 3 : 0.60 : n.d.)
		others	(O : n.d. : n.d. : n.d.)

Hence, the functionality of the *Building System* $Q_B^{Ph}(t)$ is the weight average of the functionalities of the *Building Categories* $Q_h^{Ph,B}(t)$ that are the weight averages of the functionalities of the *Building Unit Typologies* $Q_\tau^{Ph,B,h}(t)$. Analytically their expressions are the following

$$Q_B^{Ph}(t)=\frac{\sum_h w_h^{Ph,B}\cdot Q_h^{Ph,B}(t)}{\sum_h w_h^{Ph,B}};\quad Q_h^{Ph,B}(t)=\frac{\sum_{\tau\in h} w_\tau^{Ph,B,h}\cdot Q_\tau^{Ph,B,h}(t)}{\sum_{\tau\in h} w_\tau^{Ph,B,h}};$$
$$Q_\tau^{Ph,B,h}(t)=\frac{\sum_{u\in\tau} w_u^{Ph,B,h,\tau}\cdot Q_{\tau,u}^{Ph,B,h}(t)}{\sum_{u\in\tau} w_u^{Ph,B,h,\tau}}; \tag{5}$$

where h and $w_h^{Ph,B}$, τ and $w_\tau^{Ph,B,h}$, u and $w_u^{Ph,B,h,\tau}$ are the indices and the weight coefficients of the *building category*, the *building sub-categories* and the *building units* respectively; $Q_{\tau,u}^{Ph,B,h}(t)$ is the functionality of the *Building Unit* that is defined in the next paragraph in Equation (6). Suggested values of the weight indices are provided in Table 1 and they have been determined based on engineering judgment that has an important role in safety assessment.

5.2 Interdependency

The performances of the *Buildings System* cannot be determined without considering the interdependencies that in this approach have been taken into account at the *Building Unit* level. In fact, the performances of a generic *Building Unit* $Q_{\tau,u}^{Ph,B,h}(t)$ mainly depend on its structural $q_{S,u}(t)$ and non-structural $q_{NS,u}^{Ph,B,h,\tau}(t)$ functionalities. The *structural functionality* is defined as the percentage of building unit that is usable and its estimation will be discussed in the following section. Instead, the *non-structural functionality* depends on the building *typology* and on its interdependencies with utilities and on the performances of the services supplied from the building. In particular, the non-structural performances can be measured observing:

- the *quality of services received* such as water, electricity, natural gas, oil, heating, internet, etc.;
- the *quality of services supplied* that depends on the building unit typology, e.g. hospitals provide health care, police and fire stations provide assistance to citizens, power plants provide electrical power, etc.;

Hence, the definition of functionality of a *Building Unit* is provided by the following equation

$$Q_{\tau,u}^{Ph,B,h}\left(t\right)=\begin{cases}0 & \overline{q}_{\tau,u}^{Ph,B,h}\left(t\right)<U_{\tau,u}^{Ph,B,h}\\ \overline{q}_{\tau,u}^{Ph,B,h}\left(t\right) & \overline{q}_{\tau,u}^{Ph,B,h}\left(t\right)\geq U_{\tau,u}^{Ph,B,h}\end{cases};$$
$$\text{with: } \overline{q}_{\tau,u}^{Ph,B,h}\left(t\right)=q_{S,u}\left(t\right)\cdot\left[1-w_{NS,u}^{Ph,B,h,\tau}\cdot\left(1-q_{NS,u}^{Ph,B,h,\tau}\left(t\right)\right)\right] \tag{6}$$

where $U_{\tau,u}{}^{Ph,B,h}$ are the lower bound limits that define the *usability* of the building units, and $w_{NS,u}{}^{Ph,B,h,\tau}$ are the weight coefficients that define the importance of the non-structural functionality with respect to the structural functionality. Suggested values are given in Table 1. The *Usability* defines the limit between people coming back to their houses and people waiting in provisional shelters or in temporary houses.

Thus, in the methodology, nine key factors have been identified for evaluating the non-structural performances of a building unit (Table 2). These values will be analytically defined in the following section.

Table 2. Performance indicators of the non-structural functionality of a building unit.

Non-structural functionality	Key factors		Explanation
$q_{NS,u}^{Ph,B,h,\tau}(t)$	Accessibility	$q_{A,u}(t)$	the accessibility into the building unit from the transportation system.
	Water	$q_{W,u}(t)$	quality of the water supply that can be provided from the water system, wells, etc.
	Electricity	$q_{E,u}(t)$	quality of the electricity supply that can be provided from the power grid, generators, solar panels, etc.
	Natural Gas	$q_{N,u}(t)$	quality of the natural gas supply that can be provided from the gas distribution network, gas cylinders, etc.
	Oil	$q_{OL,u}(t)$	quality of the oil supply that can be provided from oil pipelines, oil tankers, etc.
	Communication	$q_{C,u}(t)$	quality of the communication system that can be provided from trasmitters, wireless routers, etc.
	Heating	$q_{H,u}(t)$	quality of the heating supply that can be provided from solar heating, heating plants, etc.
	others	$q_{O,u}(t)$	n.d.
	Performance of services supplied	$q_{P,u}^{Ph,B,h,\tau}(t)$	quality of the services supplied that depends on the type of building unit

For example, the comfort of the residents of a building unit decreases after a catastrophic event, if utilities such as water, electricity, natural gas, communication, and heating are missing. The performance of a hospital reduces if the facility is isolated or partly connected to the transportation network, because it cannot be reached from injuries and casualties. A building unit that is not accessible cannot accommodate persons or be repaired. Hence, the *non-structural functionality* is analytically defined as

$$q_{NS,u}^{Ph,B,h,\tau}(t)=\frac{w_P^{Ph,B,h,\tau}\cdot q_{P,u}^{Ph,B,h,\tau}(t)+\sum_j w_j^{Ph,B,h,\tau}\cdot q_{j,u}(t)}{w_P^{Ph,B,h,\tau}+\sum_j w_j^{Ph,B,h,\tau}} \tag{7}$$

where j is the performance index (A, W, E, N, OL, C, H, and O) and $w_j^{Ph,B,h,\tau}$ are the weight coefficients associated to each performance and are function of the type of building unit. For example, a housing unit does not offer a public service to the community, but it has a residential purpose that can be achieved when it is accessible, while its comfort depends on the quality of the utilities received ($w_A^{Ph,B,R,HU}$=50; $w_W^{Ph,B,R,HU}$=10; $w_E^{Ph,B,R,HU}$=16; $w_N^{Ph,B,R,HU}$=8; $w_{OL}^{Ph,B,R,HU}$=0; $w_C^{Ph,B,R,HU}$=10; $w_H^{Ph,B,R,HU}$=6; $w_O^{Ph,B,R,HU}$=0; and $w_P^{Ph,B,R,HU}$=0).

5.2.1 Loss and recovery functions

A performance indicator for a building unit during the transient analysis is function of time t and other parameters that depend on the type of building unit. In literature, several models describe the performance functions, which can be either *empirical* or *analytical* depending on the source of data and the type of analysis [Cimellaro et al., 2010b]. *Empirical* performance functions are based on test or real-time interpretation of field data and engineering judgment. Since the complexity of the problem changes case by case, no specific models are presented in this section. *Analytical* performance functions are developed from the community response data obtained through the analysis of the system using numerical simulations. The essential requirement of the analytical models is the simplicity, therefore the model should be selected so that it is easy to fit to real or numerical observation data and the number of parameters involved should be as low as possible. In general, in the *performance function* it is possible to distinguish three phases (see Figure 2):

- *Loss*, i.e. when the functionality drops,

- *Administrative*, which is defined as the time elapsed from the disaster time until the beginning of recovery, and
- *Recovery*, i.e. when the building is being repaired.

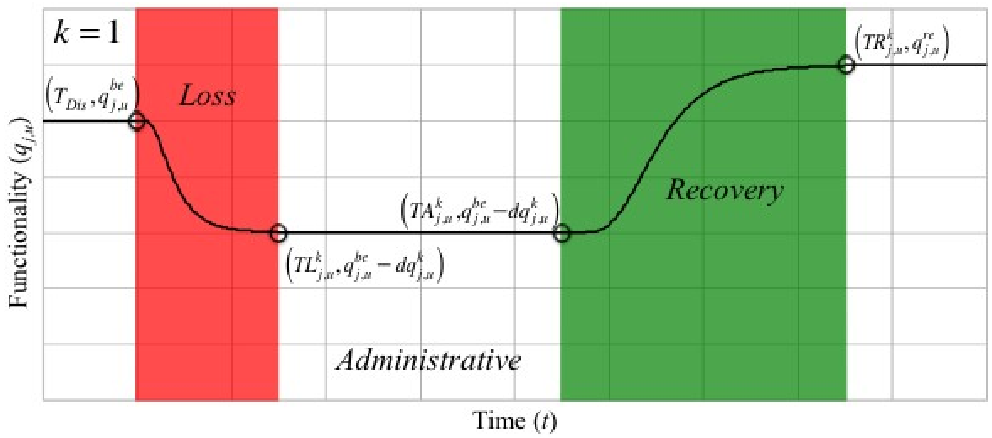


Figure 2. Typical Performance Function.

Therefore, a general formulation to evaluate the performances of an indicator $q_{j,u}(t)$ which is given by the following equation is proposed

$$q_{j,u}(t) = q_{j,u}^{be} + \sum_k \Bigg\{ dq_{j,u}^k(t) \cdot H\left(t - TD_{j,u}^k\right) \cdot \Bigg[-r_{j,u}^{I,k}\left(t, TD_{j,u}^k, TL_{j,u}^k\right) + \ldots \\ \left(\frac{q_{j,u}^{re} - q_{j,u}^{be}}{\sum_k \left[dq_{j,u}^k(t) \cdot H\left(t - TD_{j,u}^k\right) \right]} + r_{j,u}^{I,k}\left(t, TD_{j,u}^k, TL_{j,u}^k\right) \right) \cdot r_{j,u}^{II,k}\left(t, TA_{j,u}^k, TR_{j,u}^k\right) \Bigg] \Bigg\} \tag{8}$$

where $q_{j,u}^{be}$ is the functionality before the disaster; $q_{j,u}^{re}$ is the functionality after the recovery phase; k is the damage index (i.e., indicates the earthquakes sequence); $TD_{j,u}^k$ are the times of occurrence of damages, i.e. the time when a k^{th} loss has occurred; $H(t\text{-}TD_{j,u}^k)$ is the Heaviside step function, $dq_{j,u}^k(t)$ are the losses of functionality due to a certain damage k (these are given by Equation (12)), $TL_{j,u}^k$ are the time of losses, i.e. the time when a k^{th} loss has completed the drop, $TA_{j,u}^k$ are the administrative times, i.e. time when start a k^{th} recovery process, $r_{j,u}^{I,k}(t,TD_{j,u}^k,TL_{j,u}^k)$ is the loss function, $r_{j,u}^{II,k}(t,TA_{j,u}^k,TR_{j,u}^k)$ is the recovery function, and $TR_{j,u}^k$ are the recovery times, i.e. time when finish a k^{th} recovery process that is given by:

$$TR_{j,u}^{k} = TA_{j,u}^{k} + dTR_{j,u}^{k}\left(t\right) \tag{9}$$

where $dTR_{j,u}{}^{k}$ are the repair and clean-up, or construction times of the physical infrastructure unit (these are evaluated using HAZUS for building units and ATC-13 for bridges). The loss and recovery functions are analytically defined as follows

$$r_{j,u}^{\alpha,k}\left(t, T_S, T_F\right) = \begin{cases} 0 & t \le T_S \\ g_{j,u}^{\alpha,k}\left(t, x_1, .., x_n\right) & T_S < t < T_F \quad \text{with } \alpha = I,\ II \\ 1 & T_F \ge t \end{cases} \tag{10}$$

where $g_{j,u}{}^{\alpha,k}(t,x_1,...,x_n)$ has been defined as bound function, which can be any function that respects the condition given by

$$\begin{cases} g_{j,u}^{\alpha,k}\left(t, x_1, ..., x_n\right) \in C^0 \\ g_{j,u}^{\alpha,k}\left(T_S, x_1, ..., x_n\right) = 0 \quad g_{j,u}^{\alpha,k}\left(T_F, x_1, ..., x_n\right) = 1 \\ 0 \le g_{j,u}^{\alpha,k}\left(t, x_1, ..., x_n\right) \le 1 \quad \forall t \in \mathbb{R} \end{cases} \tag{11}$$

where $x_1, ..., x_n$ are the parameters involved in describing the bound function. The functionality in Equation (8) can be used for modelling both *short-term* and *long-term* recoveries. *Long-term recovery model* is used when the reconstruction phase needs to be modelled, while *short-term recovery model* is used when the emergency phase after the extreme event needs to be focused upon. The latter is performed by the overlapping of the loss phase and the recovery phase (see Figure 3), i.e. imposing $TA_{j,u}{}^{k} \le TL_{j,u}{}^{k}$.

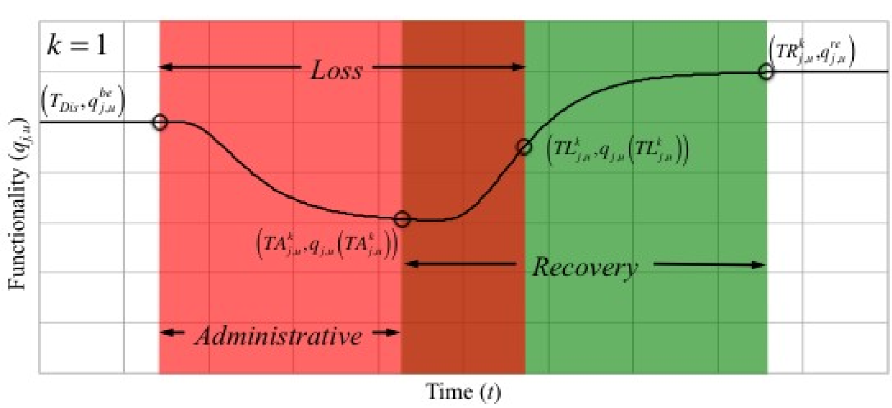


Figure 3. Overlapping between loss and recovery phases.

5.3 Losses Estimation

This section presents the methodology to estimate the *losses*, the *height of debris* that felt from buildings on the roads during an earthquake and the *accessibility of the building units*.

5.3.1 Structural Performance Function of a Building Unit

In the proposed methodology the damage states (*0=none, 1=slight, 2=moderate, 3=extensive, and 4=complete*) of building and of road network units are defined and evaluated according to the HAZUS methodology [FEMA, 2003]. Furthermore, it is assumed that there is a strong correlation between losses and probabilities of damage states (structural and non-structural). Its definition is based on the identification of the physical damages of the structural (e.g., beams, columns, walls, etc.) and non-structural (e.g., partition walls, ceilings, etc.) elements. Since the damage states, so identified, do not take into account the usability of the infrastructure, it is proposed a method to convert the damage states into functionality losses, i.e. usability losses. The *usability* of an infrastructure unit is correlated to the damage states and to its typology. For example, if a building unit is evacuated when a certain damage state is reached, a critical facility such as a hospital, that should remain functional during an emergency, might not close under the same damage state level. Hence, the structural functionality losses of a physical infrastructure unit $dq_{S,u}{}^{k}$ due to the k^{th} event are given by

$$dq_{S,u}^{k} = q_{S,u}^{k}\left(TD_{S,u}^{k}\right)\cdot\frac{\sum_{ds=1}^{ds_{\max}} w_{S,ds,u}^{Ph,B,h,\tau}\cdot PDS_{S,ds,u}^{Ph,B,h,\tau}}{\sum_{ds=1}^{ds_{\max}} w_{S,ds,u}^{x}} \qquad (12)$$

where ds is the damage state index, k is an index that identifies k^{th} earthquake into the sequence of earthquakes, $PDS_{j,ds,i,p}{}^{Ph,B,h,\tau}$ are probabilities of being in, or exceeding, a given structural damage state (function of structural features and of seismic demand), $q_{S,u}{}^{k}(TD_{j,u}{}^{k})$ is the structural functionality evaluated at $TD_{j,u}^k$ (i.e., before the k^{th} loss occurs), $w_{S,ds,u}^{Ph,B,h,\tau}$ are the weight coefficients that convert the probabilities of damage states in % of structural functionality (e.g., for a hospital it can be assumed $w_{S,1,u}^{Ph,B,H,H}$=5, $w_{S,2,u}^{Ph,B,H,H}$=10, $w_{S,3,u}^{Ph,B,H,H}$=25, and $w_{S,4,u}^{Ph,B,H,H}$=60, while for a housing unit $w_{S,1,u}^{Ph,B,R,HU}$=5, $w_{S,2,u}^{Ph,B,R,HU}$=45, $w_{S,3,u}^{Ph,B,R,HU}$=40, and $w_{S,4,u}^{Ph,B,R,HU}$=10). In particular, the loss function $r_{S,u}^{I,k}(t,TD_{S,u}^k,TL_{S,u}^k)$ is assumed with a linear bound function and has $TD_{S,u}^k$=$TL_{S,u}^k$, while the recovery function $r_{S,u}^{II,k}(t,TA_{S,u}^k,TR_{S,u}^k)$ is assumed with a cumulative lognormal bound function and as default $K_{S,u}^k$=3 (see Figure 4). Moreover, the structural functionality values before the disaster and after the recovery phase have been assumed $q_{S,u}^{be}$=$q_{S,u}^{re}$=1.

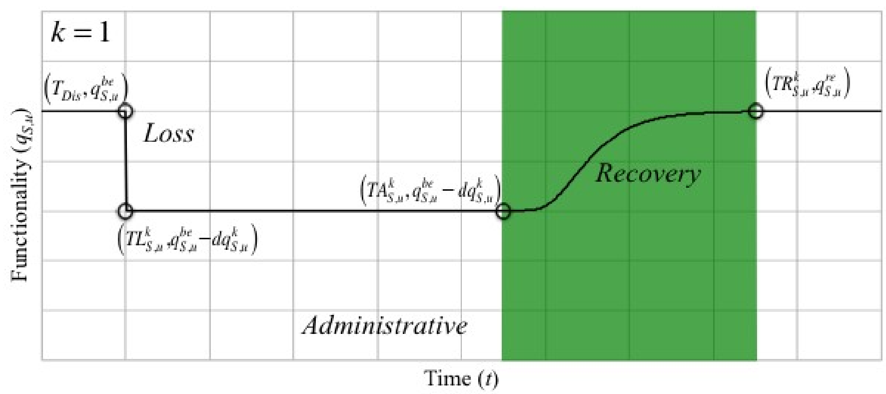


Figure 4. Structural functionality for building and road units.

5.3.2 Debris height generated by building collapse on a road network

The interdependencies in term of damage assessment between road network and a generic building unit are shown in Figure 5. In fact, a building unit, after damage, releases a certain amount of debris that can affect the normal traffic flow of the road network.

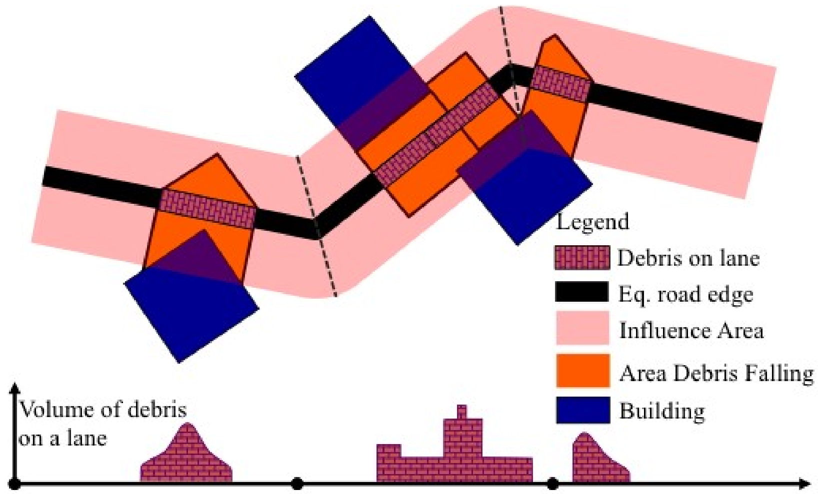


Figure 5. Interdependences in the damage assessment between road network edge and building units.

The amount of debris, which falls from a building unit, has been estimated according to the HAZUS empirical approach. Its output is the weight (tons) of two types of debris: large (such as steel members or reinforced concrete elements) and small (e.g., brick, wood, glass, building contents and other materials) pieces [FEMA, 2003]. Since the unit weight for both types of debris is equal to 1.3 ton/m^3, we have converted the two weights into a total volume (m^3) of debris $D_u^{Ph,B,h,\tau}$. The fall of debris generated from a single building unit is localized and depends on the building features and on the seismic demand. The closure of a road or a bridge occurs when all lanes are unusable. Hence, the average height of debris on the n^{th} lane $HD_{n,j}$ is evaluated summing the effects of the building units ($BIA_{e,u}$) that stay inside the influence area of the road. The effects are estimated according to the projectile motion, assuming a triangular distribution of the velocity ($v_0 \times y/H_i$; see Figure 6) and a maximum velocity v_0 at the top of the building unit equal to $S_{a,i} \times T_i/2$. Hence, $HD_{n,j}$ analytically is given by

$$HD_{n,j}^{k} = \sum_{i \in BIA_{e,u}} \int_{x_{L,n-1}}^{x_{L,n}} \int_{0}^{y_{B_i}(z)} \frac{f\left(x, y, dz \cdot j + \frac{dz}{2}\right)}{x_{L,n} - x_{L,n-1}} \cdot dy \cdot dx$$

$$\text{with: } f(x,y,z) = \begin{cases} \dfrac{D_i^{x,k}}{V_{B_i}} & x_{B_i,1}(z) \le x + \operatorname{sgn}\left(x_{B_i,1}(z)\right) \cdot \dfrac{T_i \cdot S_{a,i}}{2 \cdot H_i} \cdot \sqrt{2 \cdot \dfrac{y^3}{g}} \le x_{B_i,2}(z) \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

where x, y, and z are the coordinates that are graphically defined in Figure 6, j is the index of the strips with constant depth dz, n is the lane index, i is the building unit index, $BIA_{e,u}$ is the set of buildings that stay inside the influence area of the edge unit, $x_{L,n}$ are the limits that define the shape of the lanes, $y_{B_i}(z)$, $x_{B_i,2}(z)$ and $x_{B_i,1}(z)$ are the limits that define the shape of the i^{th} building unit at j^{th} strip, dz is the depth of the strips, $dzj+dz/2$ is the mean value in terms of curvilinear abscissa of the j^{th} strip, $f(x,y,z)$ evaluates the volume of debris that falls on the lane, V_{B_i} is the volume of the i^{th} building unit, T_i and $S_{a,i}$ are the spectral period and acceleration of the i^{th} building unit evaluated in the section, H_i is the height of the building (note that $H_i \geq y_{B_i}(z)$), and g is the acceleration of gravity.

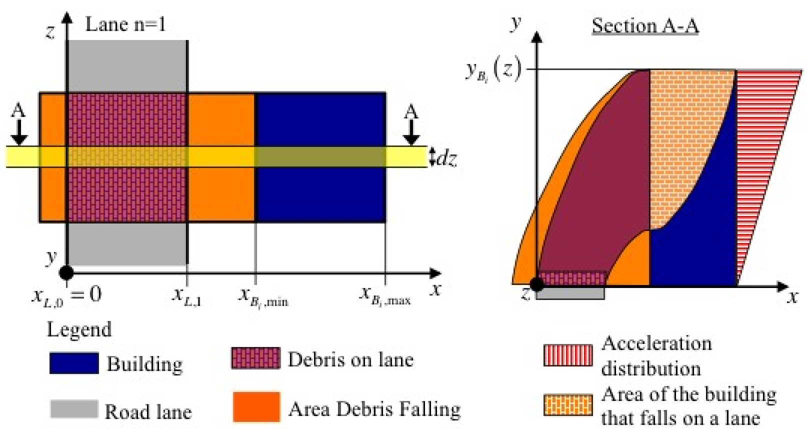


Figure 6. Geometrical definition of the debris motion.

5.3.3 Accessibility Performance Function of a Building Unit

This section focuses on the accessibility performance function $q_{A,u}(t)$ of the building units. The loss function $r_{A,u}^{I,k}(t,TD_{A,u}^{k},TL_{A,u}^{k})$ is assumed with a linear bound function and has $TD_{A,u}^{k}=TL_{A,u}^{k}=TA_{A,u}^{k}$, while the recovery function $r_{A,u}^{II,k}(t,TA_{A,u}^{k},TR_{A,u}^{k})$ is assumed with a multi-step bound function (Figure 7). The *accessibility losses* and the *accessibility values* before the disaster and after the recovery phase are assumed $q_{A,u}^{be}=q_{A,u}^{re}= dq_{A,u}^{k,\beta} =1$. Therefore, the accessibility performance function is analytically defined as follows

$$q_{A,u}(t) = \begin{cases} 1 & \text{when it is accessible} \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

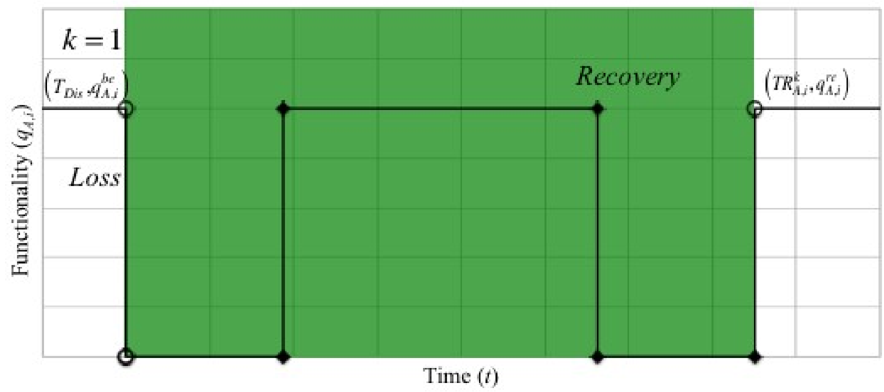


Figure 7. Accessibility performance function for building units.

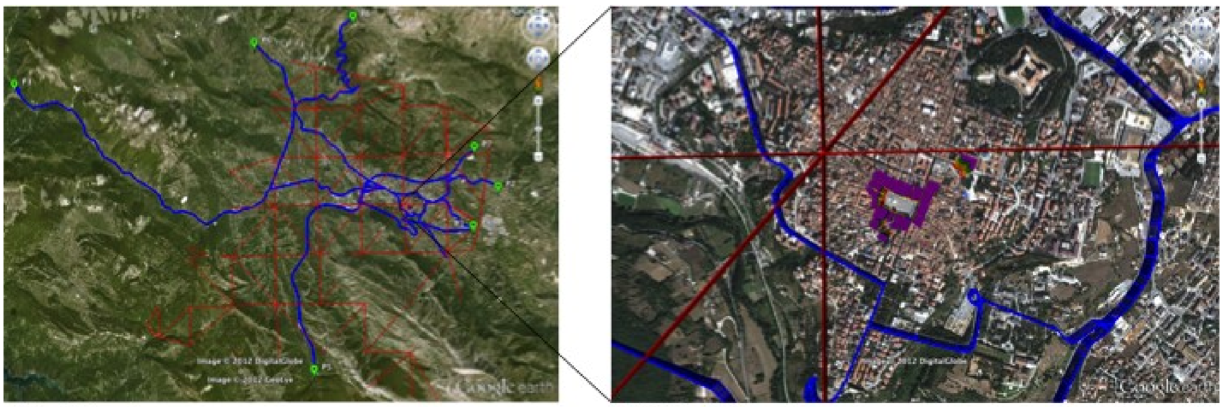
6 CASE STUDIES

The methodology has been implemented in a software, which is able to assign the damage states of the buildings and of the road network. It also evaluates a recovery plan that maximizes the resilience index with respect to physical, social, and economic constraints. The proposed model has been tested – to evaluate the interdependencies between the road network and the building system – using two case studies:

- The old medieval centre of L'Aquila town during the 2009 earthquake, and
- Treasure Island in San Francisco Bay area.

6.1 The Old Medieval Centre of L'Aquila Town during the 2009 earthquake

On April 6th 2009, the Italian region Abruzzo was affected by an earthquake with a local magnitude of 5.9 on the Richter scale (6.3 on the moment magnitude scale). The epicentre of the main shock was near the urban centre of L'Aquila (less than 10 km). The seismic action measured with the Housner Intensity parameter [Housner, 1952] was generally higher than that measured with a return period T_R of 475 years, but remarkably lowers than that with T_R of 2,475 years [Masi et al., 2011]. It is assumed that inside the selected region there are twenty-two building units near Piazza del Duomo with different features (that are not real, but are modelled with realistic features for the case study; see Table 4a). Moreover, the graph of the transportation network of L'Aquila (with the district assumption) was downloaded from the Open Street Map database [OSM , 2013]. The total length of the network is about 2,000 km. In Figure 8 are shown the B units selected in the old medieval centre (in purple) and the road network of L'Aquila (the traffic sources are the green markers, the standard roads are the blue edges, and the district roads are the red edges).



a) Road Network

b) Building Units

Figure 8. Road Network (a) and Building Units (b) near Piazza del Duomo, L'Aquila.

The seismic risk assessment has been performed with a pseudo-probabilistic hazard analysis assuming the collapse of all bridges, the debris on the roads caused by building damage; and a return period (T_R) of 1,000 years [Calvi, 2010]. The test evaluates four scenarios (i.e., *Case 1*, *Case 2*, *Case 3*, and *Case 4*) corresponding to four different boundary constraints. The recovery process for the road network is evaluated assuming that there are unlimited resources (construction workers) therefore the reconstruction phase of an edge starts when its site is accessible from the traffic source nodes. A *source* is a node, which has only outgoing flow and it is located at the intersection of the road network with the border of the region analysed. While, the recovery process for the building units is evaluated according to the boundary constraints described in Table 3. Moreover, the interdependencies between the road network and the building system have been considered assuming that a non-accessible building unit cannot be recovered.

Table 3.   Boundary constrains for the four cases.

Case:	Case 1	Case 2	Case 3	Case 4
Maximum Construction sites per day	0	1	3	No-limits
Maximum of Simultaneous Statrs of Construction sites in 7 days	0	1	3	No-limits
Economic Budget	No-limits			

The weight coefficients associated to each system of Physical Infrastructure dimension, building units, and non-structural features are assumed as follows

$$
\begin{array}{ll}
w_s^{Ph} = \begin{cases} 1 & s = T, B \\ 0 & \forall s \notin T, B \end{cases} & w_{S,j,u}^{Ph,B,h,\tau} = \begin{cases} 1 & j=0 \qquad 24 \quad j=3 \\ 5 & j=1 \qquad 60 \quad j=4 \\ 10 & j=2 \end{cases} \\
W_{NS,u}^{Ph,B,h,\tau} = 1 & w_j^{Ph,B,h,\tau} = \begin{cases} 1 & j = A \\ 0 & others \end{cases}
\end{array}
\tag{15}
$$

Table 4. Features of the building units in: (a) old medieval centre of L’Aquila and (b) Treasure Island in San Francisco Bay.

a)

Old Medieval Centre of L'Aquila Town																
Name	ArciResilience Classification			HAZUS Classification			Peak Response		Structural Damage States				Building Recovery Period [days]	Func. Losses [-]	Access. Time [days]	Debris [m³]
	System	Category	Sub-Category	Building Typology	Seismic Design Level	Type of Building	Acc. [m/s²]	Displ. [m]	Slight [-]	Moderate [-]	Extensive [-]	Complete [-]				
Building 1	Building system	Residential	Housing Units	Normal Building	Low Code	URMM	0.22	0.13	99.0%	94.0%	72.4%	35.8%	137	54.2%	0	4.60
Building 2						C1M	0.16	0.24	99.6%	96.7%	69.9%	31.6%	130	51.4%	0	11.19
Building 3					High Code	RM2L	0.71	0.03	78.4%	46.8%	10.0%	1.1%	25	12.7%	0	1.10
Building 4		Commercial	Office Buildings		Moderate Code		0.50	0.06	90.1%	74.1%	35.8%	6.6%	63	25.4%	0	2.72
Building 5							0.50	0.06	90.1%	74.1%	35.8%	6.6%	63	25.4%	0	2.53
Building 6		Residential	Housing Units			C1M	0.30	0.13	95.5%	81.8%	30.5%	7.2%	59	25.6%	0	0.87
Building 7						RM2M	0.42	0.09	90.6%	74.1%	26.3%	4.3%	52	21.9%	0	3.30
Building 8		Commercial	Hotels - Accommodations	Special Building	Low Code	URMM	0.33	0.09	96.8%	83.2%	44.8%	12.1%	81	32.2%	0	4.42
Building 9		Residential	Housing Units	Normal Building	High Code	C2M	0.55	0.07	86.2%	44.3%	3.8%	0.2%	19	10.8%	0	0.53
Building 10		Commercial	Office Buildings	Special Building	Moderate Code	RM2L	0.63	0.05	83.0%	59.0%	19.0%	2.8%	39	17.3%	0	2.19
Building 11		Residential	Housing Units	Normal Building		C1L	0.38	0.10	95.1%	84.6%	46.8%	12.7%	83	33.0%	0	5.69
Building 12						C1M	0.30	0.13	95.5%	81.8%	30.5%	7.2%	50	25.6%	0	2.98
Building 13						RM2L	0.50	0.06	90.1%	74.1%	35.8%	6.6%	63	25.4%	0	3.94
Building 14						S1M	0.23	0.20	97.6%	86.0%	45.3%	12.1%	108	32.6%	0	1.79
Building 15						S4M	0.30	0.12	94.8%	82.4%	32.8%	7.5%	64	26.4%	0	1.84
Building 16		Commercial	Distribution Facilities			S2M	0.31	0.14	95.0%	80.7%	28.5%	6.7%	90	24.6%	0	0.17
Building 17			Hotels - Accommodations			S4H	0.21	0.18	95.8%	80.9%	28.2%	5.5%	47	24.0%	0	1.55
Building 18		Residential	Housing Units			C1M	0.30	0.13	95.5%	81.8%	30.5%	7.2%	50	25.6%	0	1.80
Building 19		Cultural	Religious Institutions			RM2L	0.50	0.06	90.1%	74.1%	35.8%	6.6%	95	25.4%	0	1.47
Building 20		Commercial	Manufacturing Facilities			RM1L	0.50	0.06	88.9%	73.4%	36.2%	6.8%	64	25.5%	0	0.66
Building 21		Residential	Housing Units			S1H	0.13	0.31	97.8%	87.7%	45.7%	11.1%	81	32.3%	0	0.41
Building 22							0.13	0.31	97.8%	87.7%	45.7%	11.1%	81	32.3%	0	1.80

b)

Treasure Island in San Francisco Bay																
Name	Model Classification			HAZUS Classification			Peak Building		Structural Damage States				Building Recovery Period [days]	Func. Losses [-]	Access. Time [days]	Debris [m³]
	System	Category	Sub-Category	Building Typology	Seismic Design Level	Type of Building	Acc. [m/s²]	Displ. [m]	Slight [-]	Moderate [-]	Extensive [-]	Complete [-]				
Building 1	Building system	Cultural	Sports/Recreation Venues	Normal Building	Moderate Code	C2L	0.50	0.21	99.6%	95.9%	74.5%	37.7%	108	56.1%	40	80.75
Building 2						C2L	0.50	0.21	99.6%	95.9%	74.5%	37.6%	108	56.0%	40	56.22
Building 3			Museums	Special Building		C1M	0.44	0.23	99.2%	94.0%	53.1%	14.4%	94	36.7%	40	9.37
Building 4		Residential	Housing Units	Normal Building		C1L	0.38	0.28	99.8%	98.5%	85.6%	50.5%	167	66.7%	40	6.97
Building 5		Cultural	Religious Institutions				0.38	0.28	99.8%	98.5%	85.6%	50.5%	167	66.7%	40	5.06
Building 6			Entertainment Venues				0.38	0.28	99.8%	98.5%	85.6%	50.6%	167	66.7%	40	6.15
Building 7		Residential	Shelters			C1M	0.31	0.33	99.9%	99.0%	81.7%	36.3%	147	57.3%	40	26.40
Building 8						C1L	0.38	0.28	99.8%	98.5%	85.8%	50.8%	127	66.9%	40	20.14
Building 9		Commercial	Distribution Facilities		Low Code		0.19	0.56	100.0%	99.9%	98.4%	82.3%	163	89.0%	40	9.74
Building 10		Residential	Housing Units				0.19	0.56	100.0%	99.9%	98.4%	82.3%	217	89.0%	40	17.54
Building 11							0.19	0.56	100.0%	99.9%	98.4%	82.3%	217	89.0%	40	15.54
Building 12		Commercial	Distribution Facilities		Moderate Code		0.38	0.28	99.8%	98.5%	85.8%	50.8%	168	66.9%	40	16.60
Building 13			Manufacturing Facilities				0.38	0.28	99.8%	98.5%	85.7%	50.7%	127	66.9%	40	11.31
Building 14							0.38	0.28	99.8%	98.5%	85.7%	50.6%	127	66.8%	40	9.39
Building 15		Cultural	Entertainment Venues	Special Building		C1M	0.45	0.24	99.2%	94.1%	53.3%	14.5%	94	36.9%	40	12.70
Building 16		Commercial	Distribution Facilities	Normal Building		C2M	0.42	0.25	99.5%	96.2%	68.5%	25.5%	121	47.3%	40	19.61
Building 17			Office Buildings				0.42	0.25	99.5%	96.2%	68.5%	25.5%	93	47.3%	40	7.46
Building 18							0.42	0.25	99.5%	96.2%	68.6%	25.5%	93	47.4%	40	13.04
Building 19							0.42	0.25	99.5%	96.2%	68.7%	25.6%	93	47.4%	40	11.27
Building 20							0.42	0.25	99.6%	96.2%	68.7%	25.7%	122	47.5%	40	18.36
Building 21						C2L	0.50	0.21	99.6%	96.0%	74.8%	38.0%	36	56.3%	40	30.40

6.1.1 Seismic Risk Assessment

Figure 9 shows the discrete probabilities of the damage states for building units and the road network that are plotted on a 3-D histogram located on top of the Google Earth maps of the case study analysed. The *red edges* in the road means they are not accessible, while the *purple edges* are accessible. The debris released from the damaged building units are about 58 m^3 and do not influence the functionality of the road network, because the height of released debris per unit length on the edges involved (in this case two district roads) is less than 0.01 m. The road network, although it is damaged, it can still ensure the accessibility to the building units from the traffic sources immediately after the disaster. Hence, the administrative times of the accessibility functions for all buildings units are equal to the disaster time T_{Dis}.

a) Road Network
b) Building Units

Figure 9. Damage states for Road Network (a) and Building system (b).

Table 4a shows the distribution of the damage states in all the buildings in the selected region. The building units that have the higher damages are buildings 1 and 2. This result is easy to predict because the two buildings are normal buildings designed with low seismic design level (low code). Instead, buildings 3 and 9 suffer minor damage because they are residential buildings designed with high seismic design level (high code). In summary, the analyses show that the road network, although damaged it is still able to remain functional.

6.1.2 Resilience Assessment

As was shown in Table 3, the first and fourth cases have, respectively, the minimum (CS=CSS=0) and maximum (CS=CSS=22) availability construction building sites per day and simultaneous start of construction sites. The second case has the maximum limit of one CS and of one CSS in 7 days; while, the third case has the limit of three CS and of three CSS in 7 days. In all cases, there are no-limits on economic budget. In Table 5 are shown the administrative times, resilience indices at one and at two years of building units used for the 4 cases.

Table 5. Recovery Parameters of Old medieval Centre of L'Aquila.

Recovery Parameters of Old Medieval Centre of L'Aquila Town												
Name	Administrative Time [days]				Resilience at 365 days				Resilience at 730 days			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Building 1	inf.	67	67	0	46%	85%	85%	95%	46%	93%	93%	98%
Building 2	inf.	204	75	0	49%	68%	86%	97%	49%	84%	93%	98%
Building 3	inf.	1520	0	0	87%	87%	100%	100%	87%	87%	100%	100%
Building 4	inf.	1118	362	0	75%	75%	75%	99%	75%	75%	87%	100%
Building 5	inf.	1055	349	0	75%	75%	75%	99%	75%	75%	87%	100%
Building 6	inf.	932	286	0	74%	74%	79%	99%	74%	74%	90%	100%
Building 7	inf.	1428	472	0	78%	78%	78%	99%	78%	78%	86%	100%
Building 8	inf.	687	205	0	68%	68%	81%	99%	68%	69%	90%	99%
Building 9	inf.	0	0	0	89%	100%	100%	100%	89%	100%	100%	100%
Building 10	inf.	1480	0	0	83%	83%	100%	100%	83%	83%	100%	100%
Building 11	inf.	334	89	0	67%	68%	91%	99%	67%	84%	95%	99%
Building 12	inf.	832	25	0	74%	74%	98%	99%	74%	74%	99%	100%
Building 13	inf.	1181	409	0	75%	75%	75%	99%	75%	75%	85%	100%
Building 14	inf.	498	254	0	67%	67%	76%	98%	67%	77%	88%	99%
Building 15	inf.	768	285	0	74%	74%	79%	99%	74%	74%	89%	100%
Building 16	inf.	1339	425	0	75%	75%	75%	99%	75%	75%	85%	100%
Building 17	inf.	20	20	0	76%	98%	98%	99%	76%	99%	99%	100%
Building 18	inf.	882	39	0	74%	74%	97%	99%	74%	74%	98%	100%
Building 19	inf.	1244	412	0	75%	75%	75%	99%	75%	75%	85%	99%
Building 20	inf.	990	344	0	74%	74%	75%	99%	74%	74%	88%	100%
Building 21	inf.	606	204	0	68%	68%	81%	99%	68%	73%	90%	99%
Building 22	inf.	417	173	0	68%	68%	84%	99%	68%	81%	92%	99%

In Figure 10 are shown the Physical Infrastructure resilience indices, the time of completion of the works T_{EW}, and the Physical Infrastructure functionality values at T_{EW} for each case. The resilience index is an unbiased parameter to evaluate the performance of the recovery plan, because it is independent of the user selection of the control period. The results show that *Case 4* is the most resilient, while *Case 1* has the smallest value of resilience. *Case 2* has maximum (than the other cases) finite value of recovery time T_{EW} that is equal to 4.23 years; while *Case 4* has the smallest (0.37 years). The functionality of *Case 1* is equal to 83% because this case has no recovery works.

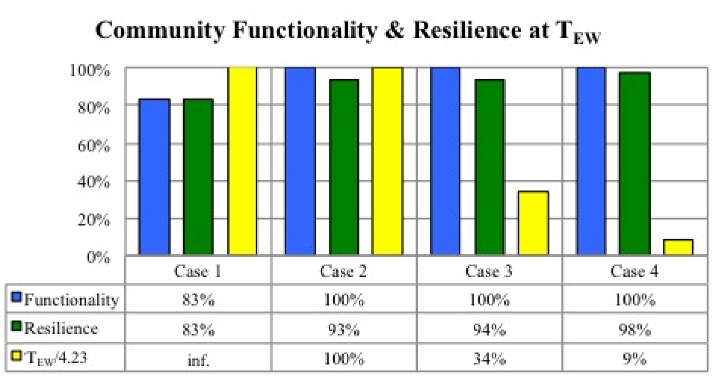


Figure 10. Resilience indices and end-work times.

The Physical Infrastructure functionality and resilience after one and two years are shown in Figure 11. The resilience value decreases with the decreasing of the velocity of recovery, so it is a good parameter to evaluate the performance of the Physical Infrastructure dimension and of the chosen recovery plan.

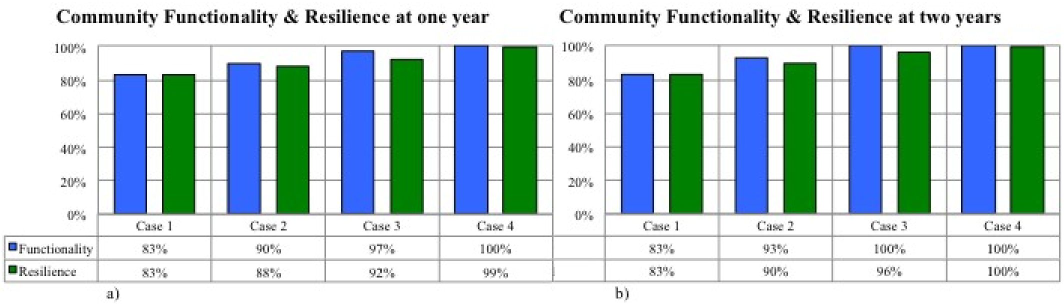


Figure 11. Functionality and resilience: at one year (a), and at two years (b).

The different results are due to the differences in the buildings sites availability (workers / day) between various cases. *Case 4* requests immediately a higher number of workers per day, while *Cases 1*, *2*, and *3* (this is the most realistic and efficient) have a stable distribution in time. The functionality curves of the Physical Infrastructure Dimension, of the Building System, and of the Transportation System are shown in Figure 12. The recovery time of the transportation system for *Cases 2*, *3*, and *4* is equal to 0.25 years.

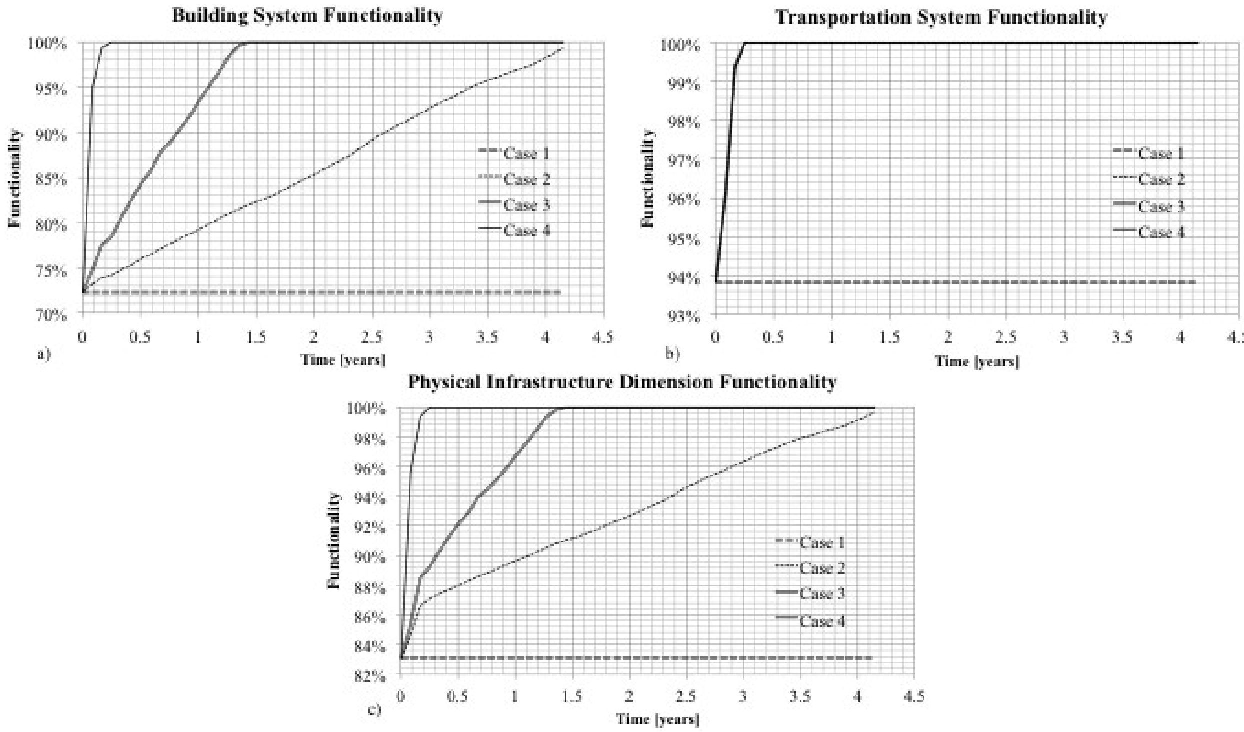


Figure 12.Recovery functions for each case of: Building system (a), Transportation system (b), and Physical Infrastructure dimension (c).

In conclusion, *Cases 2*, *3*, and *4* have similar resilience indices. *Case 4* has the smallest T_{EW}, but requests a higher number of men per day. Therefore, the most effective recovery plan is that of *Case 3*, which ensures a fast recovery with a small number of resources.

6.2 Treasure Island in San Francisco Bay area

The San Francisco Bay Area sits within the Pacific-North America plate boundary, which takes the form of multiple fault strands through the region. It has the highest density of active faults and the highest seismic moment rate per square kilometre of any urban area in the United States [WG02, 2003]. In 1906, the San Francisco Bay Area was reaching the end of a period of major seismic build-up and large earthquakes, which culminated in the great 1906 earthquake, in which approximately 3,000 persons were killed and 28,000 buildings were destroyed. Because of the stress relief due to the 1906 earthquake, the San Francisco Bay Area has been relatively quiet seismically, but a more recent study [WG02, 2003] estimated that there is a 62% probability of occurrence of an earthquake with M≥6.7 from 2002 to 2032 (Figure 13).

Figure 13.Map of the San Francisco Bay Area showing the urban areas and the probabilities of M≥6.7 earthquakes by 2032.

Therefore, Treasure Island in San Francisco Bay has been selected to observe the interdependencies between the road network and the building system, and the key role of the accessibility during the reconstruction and after a catastrophic earthquake. We have modelled twenty-one building units on the Island with realistic features (e.g. capacity curves, damping ratios, occupancy classes, repair costs etc.; see Table 4b). The graph of the transportation network of the Treasure Island (with the district assumption) was downloaded from the Open Street Map database [OSM , 2013]. The total length of the network is about of 3,000 km. In particular, the Treasure Island is connected to San Francisco and Oakland through the Bay Bridge, which is located on Highway 80. The selected building units (in purple) in Treasure Island and the road network (as above: the traffic sources are the markers in green, the standard roads are the edges in blue, and the district roads are the red edges) of the island are shown in Figure 14.

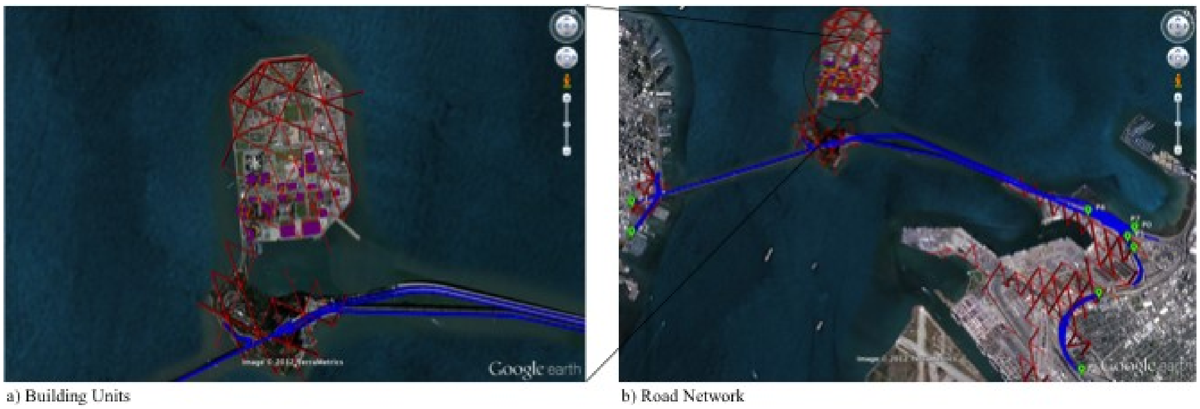


Figure 14.a) Building Units and b) Road Network in Treasure Island, San Francisco.

The interdependencies between the road network and the building system were modelled considering the *accessibility* – i.e. if a building unit is not accessible from the road network it will not be repaired and used, losing its functionality – and the *mutual damage* – i.e., if a building unit collapses in the influence area of a road, this will lose its functionality. Four different scenarios have been considered. The risk assessment has been evaluated with a pseudo-probabilistic hazard analysis assuming that all the bridges have collapsed and the seismic action has a return period of 2,450 years (i.e., it means to analyse the Ultimate Limit State). The recovery process for building units is evaluated according to the boundary constraints described in Table 3; while, for the road network is evaluated assuming unlimited resources of workers. The weight coefficients associated to each system (Physical Infrastructure dimension, building units, and non-structural features) are assumed as before (Equation (15)).

6.2.1 Risk Assessment

The discrete probabilities of damage states for building units and the functionality of the road network at the disaster time T_{Dis} are plotted in Figure 15 on a 3D histogram located on top of the map of the studied region in Google Earth. The volume of debris released from the damaged building units is of 404 m^3 and does not affect significantly the functionality of the road network; while, the collapse of the bridges makes the Treasure Island unreachable from the mainland. Therefore, the physical infrastructures on the island are not accessible, because of the collapse of the bridges that connect Treasure Island to the mainland. Hence, the building units and the district edges inside the Island are unusable, i.e. they have zero functionality.

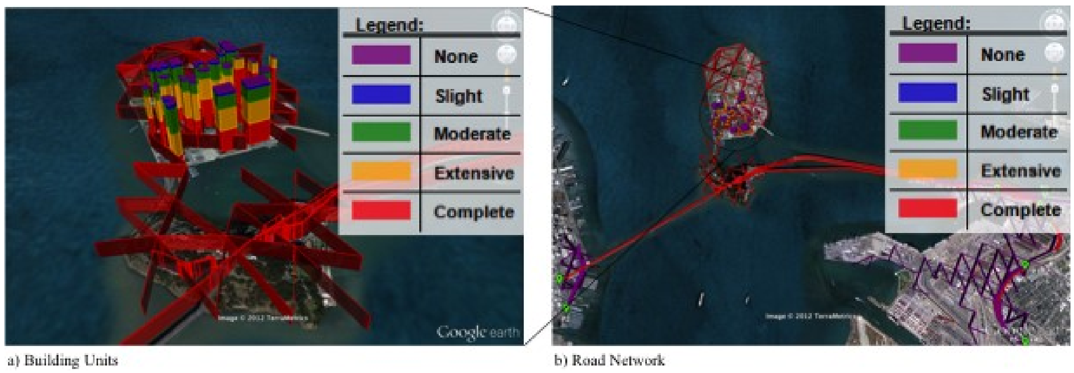


Figure 15.Discrete probability of damage states for building units (a) and functionality of the road network (b).

The detailed results of the building units inside the island are shown in Table 4b. The building units that have the lower damages are buildings 3 and 15. This result was easy to predict because the two buildings are special buildings designed with moderate seismic design level (moderate code). The most damaged building units are buildings 9, 10, and 11 that are normal buildings designed with low seismic design level (low code).

In conclusion, the bridges that connect the Island to the mainland are critical infrastructures, because with their simultaneous collapse there is no way to ensure the accessibility of the Treasure Island from the traffic sources immediately after the disaster.

6.2.2 Resilience Assessment

The restoration strategies described in this case study have the same assumptions of the previous examples. In Table 6 are shown the administrative times, the resilience indices respectively after 1 and 2 years of the building units used for the 4 cases.

Table 6. Recovery Parameters of Treasure Island in San Francisco Bay.

Recovery Parameters of Treasure Island in San Francisco Bay												
Name	Administrative Time [days]				Resilience at 365 days				Resilience at 730 days			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Building 1	inf.	1928	645	40	44%	39%	39%	85%	44%	42%	46%	93%
Building 2	inf.	2035	646	40	44%	39%	39%	85%	44%	42%	46%	93%
Building 3	inf.	40	40	40	63%	87%	87%	87%	63%	94%	94%	94%
Building 4	inf.	1446	479	40	33%	30%	30%	82%	33%	31%	51%	91%
Building 5	inf.	1614	591	40	33%	30%	30%	82%	33%	31%	41%	91%
Building 6	inf.	1279	478	40	33%	30%	30%	82%	33%	31%	51%	91%
Building 7	inf.	1781	753	40	43%	38%	38%	84%	43%	40%	40%	92%
Building 8	inf.	731	296	40	33%	29%	36%	84%	33%	31%	68%	92%
Building 9	inf.	134	133	40	11%	57%	57%	80%	11%	79%	79%	90%
Building 10	inf.	514	134	40	11%	10%	54%	77%	11%	31%	77%	88%
Building 11	inf.	297	134	40	11%	14%	54%	77%	11%	57%	77%	88%
Building 12	inf.	1111	423	40	33%	29%	29%	82%	33%	31%	56%	91%
Building 13	inf.	858	351	40	33%	30%	30%	84%	33%	31%	63%	92%
Building 14	inf.	985	352	40	33%	30%	30%	84%	33%	31%	63%	92%
Building 15	inf.	2701	900	40	63%	56%	56%	87%	63%	60%	60%	94%
Building 16	inf.	2544	847	40	53%	47%	47%	86%	53%	50%	50%	93%
Building 17	inf.	2329	40	40	53%	47%	87%	87%	53%	50%	94%	94%
Building 18	inf.	2236	40	40	53%	47%	87%	87%	53%	50%	94%	94%
Building 19	inf.	2143	754	40	53%	47%	47%	87%	53%	50%	50%	94%
Building 20	inf.	2422	758	40	53%	47%	47%	86%	53%	50%	50%	93%
Building 21	inf.	2665	880	40	44%	39%	39%	88%	44%	41%	41%	94%

In Figure 16 are shown the Physical Infrastructure resilience indices, the time of completion of the works T_{EW}, and the Physical Infrastructure functionality values at T_{EW} for each case. The results show that *Case 2*, *3*, and *4* have the same resilience, while *Case 1* has the smallest value of resilience. *Case 2* has the highest value of recovery time T_{EW} that is equal to 7.66 years; while *Case 4* has the smallest (0.70 years). The functionality of *Case 1* is equal to 21% and its recovery time is infinite, because this case has no recovery works.

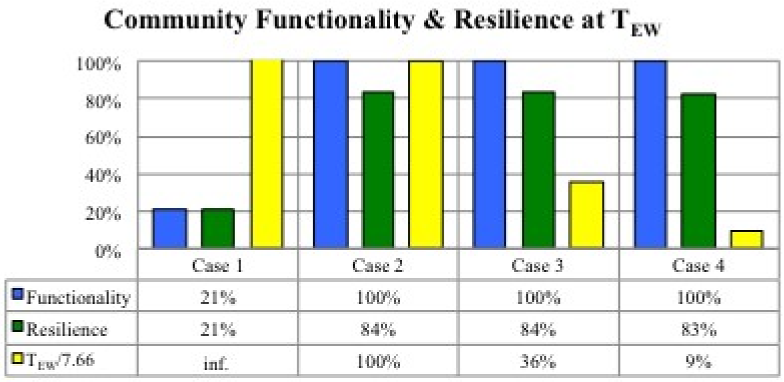


Figure 16. Resilience indices and end-work times.

The Physical Infrastructure functionality and resilience indices after one and two years are shown in Figure 17. The different results are due to the differences in the buildings sites availability (men / day) between various cases. In particular, *Case 4* is the only one that reached the complete functionality after two years.

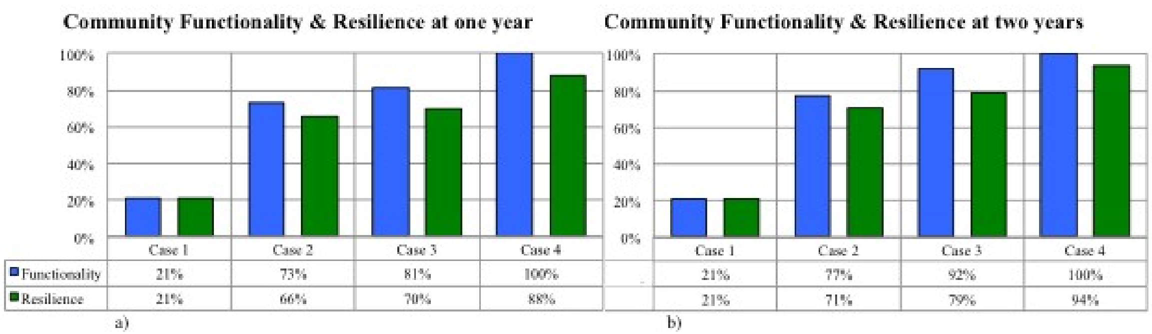
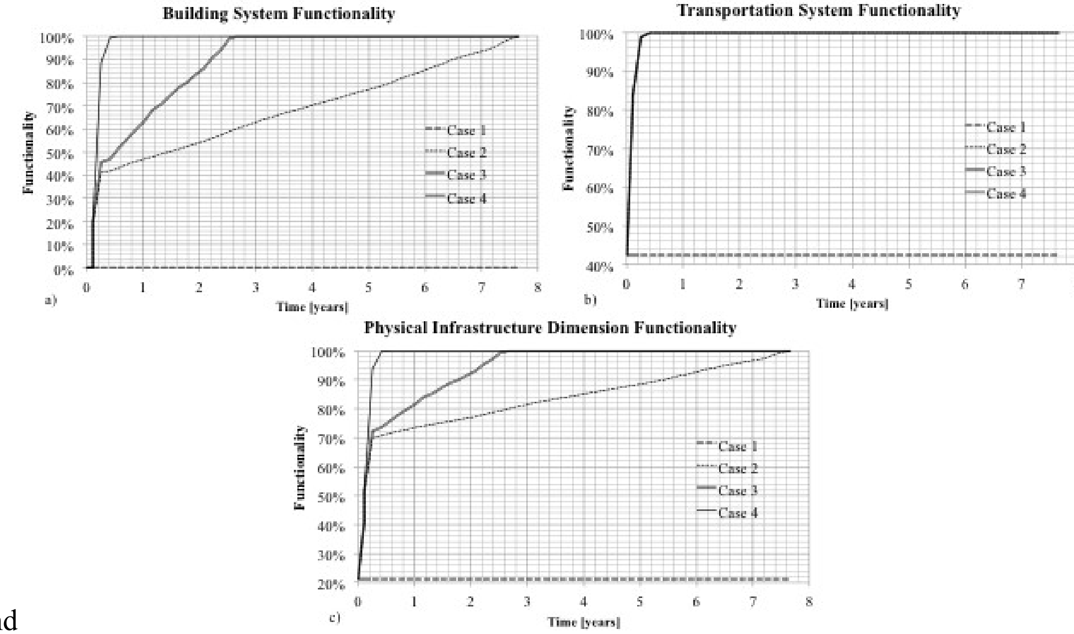


Figure 17. Functionality and resilience: at one year (a), and at two years (b).

Similarly, *Case 4* requests immediately a higher number of men per day, while *Cases 1*, *2*, and *3* (this is the most realistic and efficient) have a more homogeneous distribution in time. The functionality curves of the Physical Infrastructure Dimension, of the Building System, and of the Transportation System are shown in Figure 18. The recovery time of transportation system for *Cases 2*, *3*, and *4* is equal to 0.29 years, while, for *Case 1* is infinite.

Figure 18.Recovery functions for each case of: Building system (a), Transportation system (b),



and Physical Infrastructure dimension (c).

On 42nd day – when the first bridge that links the island to the mainland has been recovered – the functionality curves have a leap, because district roads and building units inside Treasure Island are again reachable and can be reused and/or repaired (Figure 19). Hence, the administrative times of the accessibility functions for all buildings units are equal to 42 days.

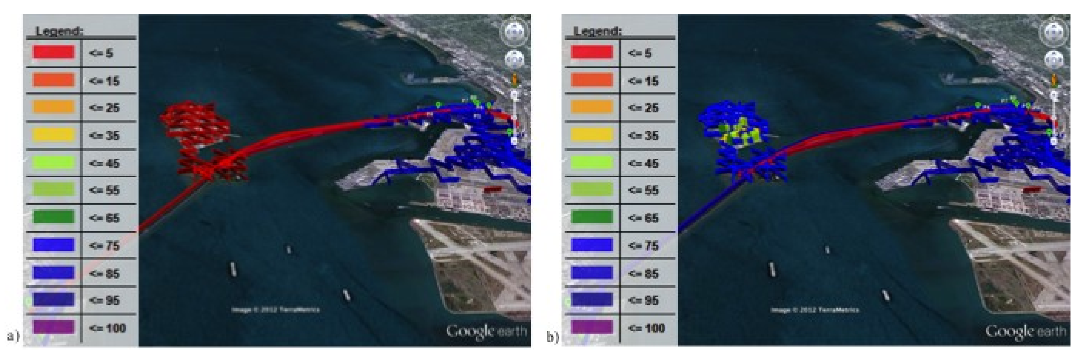


Figure 19.Functionality after the disaster time (a) and at 42th day (b).

In conclusion, as before, the most powerful recovery plan is that of *Case 3*, which ensures a fast recovery with a small number of resources. The simultaneous collapse of the bridges, which connect the island to the mainland, produced a delay of 42 days in the recovery plan. This caused a reduction of the performances of the physical infrastructures (i.e., resilience index) and an increase of the recovery times, emphasizing the importance of the accessibility of the physical infrastructures after a catastrophic event.

7 CONCLUDING REMARKS

Several areas of the world are located on critical seismic zones requiring special consideration for rescue management plans. Experience has shown that earthquake damage to the roadway network goes way beyond direct and indirect costs. The real problem are created by the extent of damage caused by lack of mobility and accessibility to devastated areas which affect post-earthquake emergency response causing further loss of life and disruption of traffic within the urban network. In fact, after an earthquake, part or most of the roadway network might be close, because of the collapse of structural elements (i.e. tunnels, bridges, etc.) and/or because of the debris from housing/building damage. Therefore, this paper presents a new method to measure disaster resilience that takes into account the interdependencies between the road networks and the building units following an earthquake event. A performance function and an analytical model are proposed to assess respectively, the performances of the physical infrastructure units and to evaluate the amount of debris, which falls from a building unit on the road. Results are compared in term of Community Resilience Indices RI and recovery time T_{EW} which are the parameters used to evaluate the performances of the infrastructures after a natural disaster.

The methodology has been implemented in a computer platform which allows an easy environment to input data and to display output directly on regional maps, letting the users see the geospatial distribution for a given hazard scenario. In addition, it has been applied to two case studies: (1) the old medieval centre of L'Aquila in Italy and (2) Treasure Island in San Francisco Bay, in California. The first case study shows how the buildings and the transportation system are modelled and discusses the community performances parameters, i.e. the resilience index RI and the recovery time T_{EW}. The second case study shows the importance of network redundancy and of the interdependencies between the physical infrastructures and the recovery services.

In conclusion, the proposed methodology can be used to develop different scenarios of road closure for different earthquake levels for example. This will allow identifying the emergency routes based on network characteristics and setting that is an essential part of developing access to devastated areas and emergency relief locations like hospitals, medical centers, shelters, warehouses, and fire stations. As outcome, an evacuation plan from the affected region can be developed.

In summary, different scenarios of urban planning can be tested with the proposed methodology and compared in term of resilience indicators by decision makers and transportation service providers. The method can be used to identify which area should receive funding priority in order to improve the performance of the transportation system during the emergency response.

8 ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEal reSCUE_637842 of the project IDEAL RESCUE - Integrated DEsign and control of Sustainable CommUnities during Emergencies.

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