Community Resilience Evaluation including interdependencies

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SUMMARY:
This paper presents a development of PEOPLES methodology to evaluate the functionality and the resilience of the transportation system, considering the interdependences between and among systems, categories, and dimensions, during extreme events. The proposed methodology considers the redundancies and the interdependencies during the entire process of damage and of recovery. The accessibility of a transportation network (and consequently to buildings units influencing their functionality) form the transportation sources is the main parameter that defines the functionality of the transportation system. This method was implemented in a software that is able to evaluate the damage state and the resilience of the road network and of the building system of a community. It provides to evaluate a recovery plan that maximizes the resilience index respecting the physical (accessibility), social, and economic limitations. Finally, the software has been tested using a case study of Treasure Island in San Francisco considering a probabilistic earthquake' risk assessment.

Keywords: Resilience, Decision-making, Disaster, Recovery plan, Transportation system, Railway, Airport, Waterway, and Road network.

1. INTRODUCTION

The disaster community resilience 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 and 2007). In the last deccade numerous catastrophic events have shown that the transportation system is a key point for a community affected by a disaster, because it is vital for emergency services such as policeman, firefighters, health care facilities, etc.. Hence, the concept of resilience has gained attention, because small damages can become catastrophes when the communities have no access to the emergency services.
Previous methodologies studied single components of the transportation system (i.e. road network, railway, waterways, airports, etc.) focusing on the concept of risk assessment that analyzed only the disaster time neglecting the recovery phase. Hence, societies are turning their attention to increase the resilience of entire communities against various types of extreme events. Moreover, communities are getting aware that they cannot prevent every risk, but rather they must learn to adapt and manage risks in the fastest way that minimizes impact on human and other systems.
The paper focuses on the transportation network and answers to several questions: how is it possible to model the transportation system and its damage states? How can redundancies' network typology be modeled? How can be modeled interdependencies with the other elements of the community? Which are the performances of the transportation network during an extreme event? And how do we model functionality and resilience?
The proposed a methodology is able to assess the damage states and evaluates the resilience index of the transportation system and of the physical infrastructures during an extreme event, following the PEOPLES framework (Renschler et al. 2010). Finally it has been implemented in a software

(Arcidiacono *et al.* 2011), which is able to assist decision-makers to prevent and minimize the disasters effects.

2. LITERATURE REVIEW

In literature are available several methods which are able to evaluate the effects of different hazards on different types of infrastructures. Among them one of the most popular is *HAZUS method* (Whitman et al. 1997) that was developed by the National Institute of Building Sciences (NIBS) and used by FEMA in 1997 to assess the earthquake losses within the US territory. The method works on inventory of the classification of various components such as population, buildings, transport systems, lifeline utilities, and hazardous materials. This method 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. The losses are provided in probabilistic terms evaluating causalities, shelters, inundations, fires, debris, hazardous material releasescime, damage states of physical infrastructure, and economic losses. The methodology considers all type of hazards, but not all the interdependencies among the structural components. For example, the damage of the transportation network generated by the building debris is not considered. Furthermore, the methodology is not considering the recovery phase; therefore it is a useful tool to design urban areas for example and prevent damages, but it is not able to manage communities during catastrophic events and design proper recovery plans.

Miles et al. (2006, 2011), after Kobe earthquake, have proposed a methodology that identifies the performance of the road network through three different indices. These are defined as the ratio between the post- and pre- event conditions of the network identified by: (*i*) *length of available roads*, (*ii*) *minimum travel distance* between the nodes of the network, and (*iii*) weighted *minimum travel distances of different subareas*. Bocchini et al. (2010, 2011) have proposed an index to define the road network functionality that is entirely based on a single parameter, which characterizes the entire network considering the status of the road network and its economic aspects. The evaluation of the functionality of the whole network is performed through two parameters: the *distance* and the *total travel time* spent on the network. However, both methodologies do not consider the travel path in both directions for a given road link and the *accessibility* of the network.

In this paper have been followed the general definition of Resilience provided by Renschler et al. (2010) that subdivides Resilience in seven dimensions according to the acronyms PEOPLES (*P*: Population and demographics; *E*: Environmental/Ecosystem; *O*: Organized governmental services; *P*: Physical infrastructure; *L*:Lifestyle and community competence; *Eco*: Economic development; and *S*: Social-cultural capital).

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.

The framework defines the functionality of each dimension considering the geospatial-temporal distribution, the interdependencies, and the redundancies. Then resilience *R* is analytically defined as follows:

$$R(\vec{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(t) / T_{LC}\, dt \quad ; \qquad Q_{TOT}(t) = f\left(Q_P, Q_{Env}, Q_O, Q_{Ph}, Q_L, Q_{Eco}, Q_S\right) \tag{1}$$

where T_{LC} is the control time of the period of interest, $\vec{r}$ is a vector defining the position within the selected region where the resilience index is evaluated, $Q_{TOT}(t)$ is the global functionality of the region considered, and Q_x is the functionality of each of the seven dimensions. The paper focuses on the Transportation system of the Physical Infrastructure dimension and its implementation issues.

3. PROPOSED METHODOLOGY

The methodology intends to analyze the transportation system of a community during catastrophic events, evaluating its resilience index and considering redundancies and interdependencies among categories and resilience dimensions. In this paper, resilience index corresponds to the area underneath

the global functionality function of the community evaluated over a control period (e.g. the recovery period until the reconstruction phase ends (T_{EW})).
Functionality of the transportation system depends on the interdependencies among different dimensions and categories. For example, the debris of a damaged building might prevent access to a road and consequently to some areas of the community, thus excluding all emergency interventions. Another example is the bridge collapse that not only interrupts the transportation network, but it can also interrupt the electric network, the gas and the water supply system that run on the bridge, so without water and electricity, critical facilities such as hospitals cannot effectively perform their primary functions. Additionally damage of subway stations, power grid etc. can also reduce or stop functionalities of subway systems, of electric railway systems etc.. Hence, all these examples show that functionality of one component is NOT only a function of the damage state itself, but it also depends on the boundary conditions provided by the other components. Moreover, economic losses, during the recovery, may involve a slower recovery process, which corresponds to a reduction of the resilience index.
The transportation system is composed by three categories: *transportation network systems* (road network, bus network, railway, subway, etc.), *ports*, and *airports* (these for incoming traffic flow). The transportation networks depend on the structural functionality of the network, on the traffic sources (internal and boundary sources), and on the functionality of the facilities connected to the network typology. Two categories of the transportation network systems can be identified: self-reliant (road network, bus network, etc.) and reliant (electric railway, subway, etc.). The *internal sources* are buildings and/or structures (airports, railway stations, ports, etc.) that contribute with an incoming flow, while, the *boundary sources* are points of the transportation network that stay on the boundary of the selected area and identify an incoming traffic flow. The buildings of the internal sources as well as the buildings of the transportation facilities are not an isolate system but they are interdependent with other services (water, electricity, heating, etc.).

3.1. Transportation System Models

The transportation system is divided in categories and sub-categories, to take into account different interdependences as follows.

Component	Category		Sub-category	
Transportation System	Ports (small, medium, large)		Waterfront Structures	
			Facilities	Cranes/Cargo Handling Equipment
				Ferry Terminals
				Dispatches
				Fuel Structures
				Maintenance
				Werehouses
				other
	Airports (small, medium, large)		Runways	
			Facilities	Control Towers
				Terminals
				Parking Structures
				Fuel Structures
				Maintenance and Hangars
				other
	Network Systems	Road Network	Network	Bridges
		Bus Network		Tunnels
		Railway System		Roads/Trucks/etc.
		Light Rail		Districts
		Subway System		Transportation Sources
		other		other
			Facilities	Monitoring Center
				Stations
				Dispatches
				Fuel Structures
				Maintenance
				other

Figure 1. Transportation system typologies (categories and sub-categories).

The airports, ports, and transportation facility structures are modeled as buildings, while the networks

are modeled with graph theory using nodes and edges. The edges are the system's components (i.e. bridges, tunnels, major roads, districts, etc.), while the nodes are the junctions between them.
Nodes and edges if near the transportation source can be used as traffic sources. The structure of the typology network T is defined by the adjacency matrix $\mathbf{A}^T(t)$, where rows and columns are the nodes, while the values are the weight coefficients of the edges.

$$A_{h,j}^T(t) = L_i^T(t) = \text{equivalent edge length} = \begin{cases} l_i \cdot nl_i(t) & \text{standard edge} \\ \sum_{j=RIA_i} l_j \cdot nl_j(t) & \text{district edge} \end{cases} \tag{2}$$

where the indices h,j correspond to the position of the ith edge in the adjacency matrix (if $\mathbf{A}^T{}_{h,j}$ is greater than zero, the edge is open, otherwise it is closed); L_i^T is the *equivalent edge length* defined as the length of the lanes inside the influence area of the respectively edge; l_i=average length of lanes of the ith component; $nl_i(t)$=number of available lanes; and RIA_i = roads inside the influence area (IA_i).
The influence area IA_i for standard edges (e.g. bridges, tunnels, railway, major roads, etc.) is rectangular (Figure 2a), while for district edges – that are a discretization of redundant sub-networks such us the secondary roads inside the towns – is rhomboidal (Figure 2b). The district edges are modeled with an *equivalent edge length* in order to reduce the computational time.

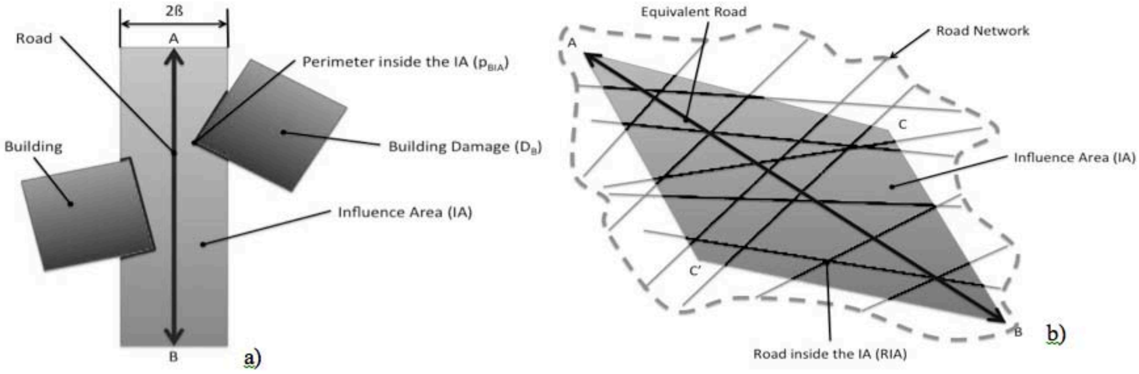


Figure 2. Equivalent edge length for standard (a) and district (b) edges.

Instead, the number of available lanes along the edge $nl_i(t)$, i.e. the edge functionality, is analytically defined as:

$$nl_i(t) = \begin{cases} f_i(t) & f_i(t) \geq L_i \\ 0 & f_i(t) < L_i \end{cases} \tag{3}$$

where $f_i(t)$ is the number of available lanes (decimal), and L_i is a lower bound limit that is function of the lane typology (e.g. road: L_i=70%, district: L_i =50%, and railway truck: L_i =100%). For example, the vehicles of firefighters (or ambulances, police cars, etc.), during the emergencies, can use a road lane with functionality less than one – this means that the entire road is not closed –, while a railway lane can be used by trains only if its functionality is 100%. The recovery curve for the number of available lanes $f_i(t)$ consists of two parts: the first is constant, while the second part has a lognormal shape. The function is analytically defined as follows:

$$f_i(t) = \begin{cases} nl_i\left(T_{Dis}^-\right) & t < T_{Dis} \\ nl_i^{Dis} & T_{Dis} \leq t \leq T_i^{Ad} \\ nl_i^{Dis} + \left(1 - nl_i^{Dis}\right) \cdot r_i\left(t - T_i^{Ad}\right) & t > T_i^{Ad} \end{cases} ; \quad r_i(t) = \frac{\sum_{k=1}^{4} w_k \cdot PDS_{i,k}^R \cdot \Phi\left(\frac{\ln(t) - \mu_k}{\sigma_k}\right)}{\sum_{k=1}^{4} w_k \cdot PDS_{i,k}^R} \tag{4}$$

where: T_i^{Ad} = the administrative time defined as the time elapsed from the disaster to the start of repair works of the edge according to the accessibility; T_{Dis} = the disaster time defined as the time when the disaster occurred; $r_i(t)$ = restoration value; Φ = the lognormal function; σ and μ, are respectively the standard deviation and average value of the lognormal distribution (given by HAZUS database).

3.2. Structural Damage Assessment

The methodology works with any risk assessment, but this paper will focus on earthquake damage assessment. HAZUS methodology has been chosen to evaluate the damage states of buildings, bridges, tunnels, etc.. It identifies the damage states probabilities ($PDS_{i,k}^T$ where: k is the index of damage states 1: slight, 2: moderate, 3: extensive, and 4: complete) as function of structural features of the peak ground acceleration (PGA_i).

$$PDS_{i,k}^{T} = f\left(PGA_i, "\ldots"\right) \tag{5}$$

Instead, the damage states of other edges (railway, major roads, districts, etc.) essentially depend on the debris of the damaged buildings that slow down the normal flow on the lanes. In detail, the closure of an edge can be caused by damage to a single building, while for district edges, being more redundant, depend on the average damage of the buildings inside the influence area that is weighted with the buildings perimeter p_j and the length of the lanes l_j inside the influence area (IA_i). Hence, the damage states are defined as follows:

$$PDS_{i,k}^{T} = \begin{cases} \max\left(PDS_{j,k}^{B} \in BIA_i\right) & \text{standard edge} \\ \dfrac{\sum_{j=BIA_i} p_j^B \cdot PDS_{j,k}^B}{\sum_{j=RIA_i} l_j} \le 1 & \text{district edge} \end{cases} \tag{6}$$

where: $PDS_{j,k}^B$ are the damage states probabilities of the buildings; BIA_i are the buildings inside the influence area; and p_j^B is the perimeter of the relative building inside the IA_i. Therefore, the number of available lanes of the edge after the disaster (nl_i^{Dis}) is analytically defined as follows:

$$nl_i^{Dis} = nl_i\left(T_{Dis}^{-}\right) \cdot \left(1 - \frac{\sum_{k=0}^{4} w_k \cdot DPDS_{i,k}^T}{\sum_{k=0}^{4} w_k}\right) \qquad \begin{cases} DPDS_{i,k}^T = 1 - PDS_{i,k+1}^T & k = 0 \\ DPDS_{i,k}^T = PDS_{i,k}^T - PDS_{i,k+1}^T & k = 1,2,3 \\ DPDS_{i,k}^T = PDS_{i,k}^T & k = 4 \end{cases} \tag{7}$$

where: k is the index of damage states (0: none; 1: slight; 2: moderate; 3: extensive; and 4: complete); w_k are weight coefficients defined in the case study as: w_0= 0, w_1= 0.1, w_2= 0.2, w_3= 0.3, and w_4= 0.4 in order to give more importance to severe damage states involving more debris; $nl_i(T_{Dis}^-)$ is the number of available lanes before the disaster time T_{Dis} (for district edge assumption is equal to 1); and $DPDS_{i,k}^T$ are the discrete probabilities of damage states.

3.3. Functionality of Transportation Networks During a Disaster

Performance of a road network can be measure using: (i) the number of immediately *available* edges after the disaster, (ii) the *accessibility* of the network (i.e. the possibility to reach a zone from the transportation sources), (iii) the traffic flow during the disaster event (which is difficult to determine during the disaster due to lack of information), and (iv) the travel time (a good parameter to evaluate the functionality in normal operating conditions, but it is not meaningful during catastrophic events).

The proposed model to measure network functionality adopted in this paper was inspired by the human circulatory system, where the transportation sources are comparable to the heart, while the network is equivalent to the blood vessels. The capacity $C^T(t)$ of the network is defined as the *equivalent length* of the network that is available and accessible from the transportation sources with functionality greater than zero:

$$C^T(t) = \text{Capacity} = \sum_{i=N_{AR}} L_i^T(t) \tag{8}$$

where N_{AR}= number of available edges and $L_i^T(t)$= equivalent edge length defined in Equation (2). The accessibility (alternative routes, etc.) and the related recovery plan are evaluated studying the relation between the adjacency matrix $\mathbf{A}^T(t)$ and the traffic sources. For example, during an emergency, the traffic directions are no longer respected, because traffic is rearranged in order to cover the weaknesses of the network. Hence, if the functionality $f_e^N(t)$ of the network typology is below a certain threshold, the adjacency matrix will be considered symmetric (both directions of traffic of the roads are allowed). The functionality is defined as the ratio between the capacities of post-disaster $C^T(t)$ and pre-disaster $C^T(T_{Dis}^-)$ as follow:

$$f_e^N(t) = \text{Network Functionality} = \frac{C^T(t)}{C^T\left(T_{Dis}^-\right)} \tag{9}$$

3.4. Functionality of the Transportation Categories During a Disaster

The subdivision of the transportation system in categories (*P1, P2, P3*: Ports, *A1, A2, A3*: Airports, *R*: Road Network, *B*: Bus Network *Rw*: Railway, *LR*: Light Rail, *S*: Subway, and *O*: Other) and sub-categories (e.g. for the networks *N*: Network, *MC*: Monitoring Center, *S*: Stations, *D*: Dispatch, *F*: Fuel Structures, *M*: Maintenance Structures, and *O*: Other) permits to evaluate the *redundancy rate* of the *building categories* showing which are the critical infrastructures. The building category functionality $Q_h^{TC}(t)$, according to interdependencies and redundancies, has been defined as follows:

$$Q_h^{TC}(t) = \frac{\sum_{e=TC_h} w_{e,h}^{TCe} \cdot f_e^E}{\sum_{e=TC_h} w_{e,h}^{TCe}} \quad \text{with } f_e^E = \begin{cases} 0 & f_e \le L_e^{CF} \\ f_e & f_e > L_e^{CF} \end{cases} \tag{10}$$

where: h is the transportation category index; TC_h are the transportation system elements that belong to the h[th] transportation category; $w_{e,h}^{TCe}$ are the weight coefficients that identify the importance of a transportation system with respect to other systems that belong to the same transportation typology h^{th} (e.g. a small airport has w^{TCe}=3, while a large airport has w^{TCe}=10); L_e^{CF} is a lower bound limit that is function of the system transportation element e^{th} (e.g. for small airports L_e^{CF} = 60%, while for large airports L_e^{CF} = 30%); and f_e is the functionality of the element transportation system defined as follows:

$$f_e = \begin{cases} f_e^N(t) \cdot \left[L_e^{CF} \cdot f_e^{CF}(t) + \left(1 - L_e^{CF}\right)\right] \cdot \left[L_e^F \cdot f_e^F(t) + \left(1 - L_e^F\right)\right] & \text{Networks} \\ f_e^{MS}(t) \cdot \left[L_e^{CF} \cdot f_e^{CF}(t) + \left(1 - L_e^{CF}\right)\right] \cdot \left[L_e^F \cdot f_e^F(t) + \left(1 - L_e^F\right)\right] & \text{Ports and Airports} \end{cases} \tag{11}$$

where L_e^F and L_e^{CF} are coefficients that identify the importance of facilities and critical facilities (e.g. the electricity supply system in the tram system controls 100% of the system functionality so L_e^{CF}= 100%) respectively; f_e^{MS}, f_e^{CF}, and f_e^F are the functionalities of the main structures (e.g. waterfront structures, runways, etc.), of the critical facilities, and of the facilities respectively which are analytically defined in the equations below:

$$f_e^{CF}(t) = \frac{\sum_{f=CF_e} \left(w_{e,f}^{CF} \cdot \frac{\sum_{j=CFB_f} w_{e,f,j}^{CFB} \cdot f_j^B}{\sum_{j=CFB_f} w_{e,f,j}^{CFB}} \right)}{\sum_{f=CF_e} w_{e,f}^{CF}} \le 1 \quad f_e^{MS}(t) = \frac{\sum_{f=MS_e} w_{e,f}^{MS} \cdot f_f^B}{\sum_{f=MS_e} w_{e,f}^{MS}} \le 1 \quad f_e^F(t) = \frac{\sum_{f=F_e} \left(w_{e,f}^{F_e} \cdot \frac{\sum_{j=FB_f} w_{e,f,j}^{FB} \cdot f_j^B}{\sum_{j=FB_f} w_{e,f,j}^{FB}} \right)}{\sum_{f=F_e} w_{e,f}^{F}} \le 1 \tag{12}$$

where: f_j^B =functionality of the j^th building; CF_e, F_e, and MS_e are respectively the critical facilities, the facilities, and the main structures that belong to the e^{th} system transportation element; FB_f, and CFB_f are the *building facility* and *critical facility* that belong to the f^{th} facility's typology respectively ; $w_{e,f}^{CF}$ and $w_{e,f}^{F}$ are the weight coefficients of facility's typologies (e.g. for a road network, L_e^F=8% and L_e^{CF}=0% because is self-reliant system without critical facilities and it has $w_{e,MC}^{F}$=20, $w_{e,S}^{F}$=0, $w_{e,D}^{F}$=10, $w_{e,F}^{F}$=60, $w_{e,M}^{F}$=10, and $w_{e,O}^{F}$=0); and $w_{e,f,j}^{CFB}$, $w_{e,f,j}^{FB}$, and $w_{e,f}^{MS}$ are the weight coefficients of building typologies (that depend on the dimension and importance of the j^{th} structures with respect to the f^{th} group).

3.5. Functionality and Resilience of the transportation system

The resilience value of the transportation system R_T^{Ph} is the integral of its functionality $Q_T^{Ph}(t)$ over a control period T_{LC} and it is given by:

$$R_T^{Ph}(T,T_{LC})=\frac{\int_T^{T+T_{LC}} Q_T^{Ph}(t)\cdot dt}{T_{LC}} \quad \text{with } Q_T^{Ph}(t)=\frac{\sum_h w_h^{TC}\cdot Q_h^{BC}(t)}{\sum_h w_h^{TC}} \tag{13}$$

where: h is the transportation category index, and w_h^{TC} are the weight coefficients for each transportation category that depend on the community system, (e.g. for normal condition w_P^{TC}=8, w_A^{TC}=12, w_R^{TC}=40, w_B^{TC}=3, w_{Rw}^{TC}=8, w_{LR}^{TC}=6, and w_S^{TC}=4; while, for an island w_P^{TC}=15, w_A^{TC}=20, w_R^{TC}=40, w_B^{TC}=3, w_{Rw}^{TC}=8, w_{LR}^{TC}=6, and w_S^{TC}=4).
Therefore, the global resilience G_R^{Ph} and the global functionality Q_{Ph} of physical infrastructure dimension are defined as follows:

$$G_R^{Ph}(T,T_{LC})=\frac{\int_T^{T+T_{LC}} Q_{Ph}(t)\cdot dt}{T_{LC}} \quad \text{with } Q_{Ph}(t)=\frac{\sum_c w_c^{Ph}\cdot Q_c(t)}{\sum_c w_c^{Ph}} \tag{14}$$

where: w_c^{Ph} is the weight coefficient associates to the c^th component. Finally the global resilience index GI_R^{Ph} and the resilience index of the transportation system I_T^{Ph} are the resilience value at the end of the recovery works T_{EW} (i.e. when the global functionality reaches 100%) starting from the disaster time T_{Dis}.

$$GI_R^{Ph}=G_R^{Ph}(T_{Dis},T_{EW}) \quad I_R^{Ph}=R_T^{Ph}(T_{Dis},T_{EW}) \tag{15}$$

In conclusion, the proposed methodology uses as main parameters for evaluating the performances of the physical infrastructure dimension, the global resilience index GI_R^{Ph} and the recovery time T_{EW}.

4. CASE STUDIES

The proposed methodology was tested – evaluating the interdependencies between road and building networks – in the case study of Treasure Island in San Francisco Bay in California. The optimal solution of the recovery plan was selected performing a sensitivity analysis.
Different recovery plans were compared in terms of resilience under certain boundary conditions (accessibility, economic budget, number of construction sites, etc.) varying also the administrative times T^{Ad}_i of each element of the model. The final outputs are: (i) the resilience index, (ii) the functionality values, and (iii) the optimal recovery plan of the analyzed system.

Figure 3. Buildings in Treasure Island, San Francisco Bay.

Treasure Island in San Francisco Bay has been selected as case study, to observe the interdependencies between the road network and the building system. The road network (data form Open Street Map database, OSM) and twenty-five residential buildings (in white in Figure 3) with realistic features (e.g. capacity curves, damping ratios, occupancy classes, repair costs etc.) have been modeled. In particular, the island is connected to San Francisco and Oakland through the Bay Bridge. The interdependencies between the road network and the building system were modeled considering the *accessibility* – i.e. if a building unit is not accessible from the road network it cannot be repaired, losing its functionality – and on the other side if a building unit collapses within the road influence area, this will lose its functionality. Moreover, for the case study it is assumed: (*i*) an earthquake with a return period (T_r) of 2450 yrs; (*ii*) no-limit on the economic budget (*EB*); (*iii*) maximum of three simultaneous starts of construction building sites (*CSS*) during the recovery phase; and also (*iv*) maximum of three construction sites per day (*CS*).

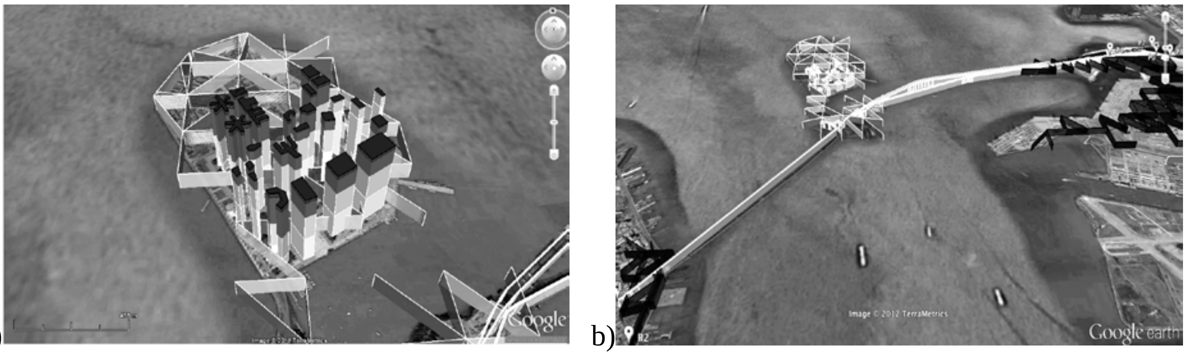
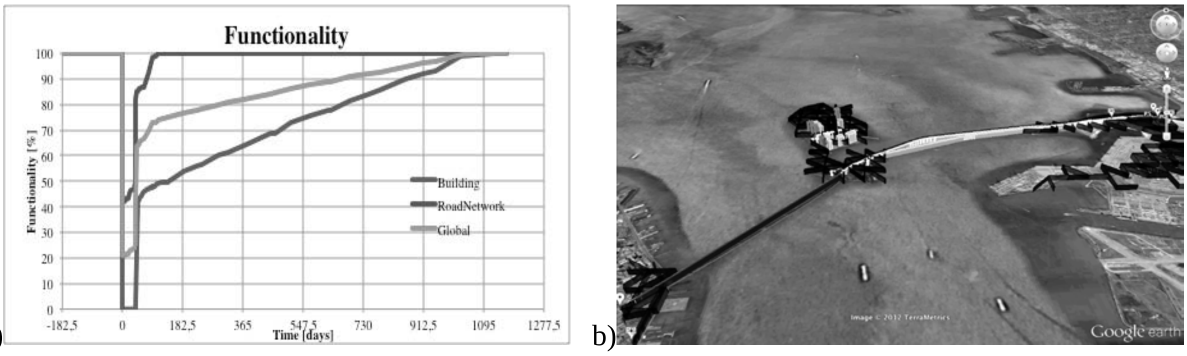
a) 

Figure 4. a) Discrete probability of damage states for buildings. b) Functionality after the risk assessment.

The discrete probability damage states for the buildings inside the island are shown in Figure 4a with a 3D histogram plotted on Google Earth (in black no damage, in white collapse or unusable). The functionality of the buildings and the entire road network, immediately after the disaster, are shown in Figure 4b. Initially, the entire Island is not accessible, because the bridges that connect it to the mainland collapsed. Hence, the building units and the district edges inside the Island are unusable, i.e. they have zero functionality.



a) b)

Figure 5. a) Functionality curves. b) Functionality after the recovery of the first bridge in the Bay area.

The functionalities of the components of physical infrastructure dimension (transportation system and building system) and its global functionality Q_{Ph}, which was evaluated with equal weight coefficients w_c^{Ph} for the road network and the building system, are shown in Figure 5a. When the first bridge that joints the island with the mainland is recovered (in 40 days according to the simulations) the global functionality has a leap, because the road network and the building units inside the island can be reused and repaired (Figure 5b). In conclusion, the results of analysis are: a recovery time T_{EW} for the community of 3.19 yrs.; resilience indices of 74.34% and 97.52% for building system and transportation system respectively; and a global resilience index equal to 85.93%.

5. CONCLUSIONS

The methodology presented in this paper describes the performance of the road network including interdependencies with buildings during extreme events such as earthquakes. The method is embedded within a more general framework called with the acronyms PEOPLES, which has been developed to assist decision makers during the post-disaster emergency response as well as during the long term reconstruction phase. It is able to evaluate the damage states, the recovery time and the Resilience index of the transportation network which is one component of the physical infrastructure dimension.
The approach models the interdependencies between categories and dimensions and it evaluates the optimal recovery plan that maximizes the resilience index of the physical infrastructure GI_R^{Ph} (considering the building and transportation systems) minimizing the recovery time T_{EW}, with respect to physical, social, and economic constraints. The proposed methodology has been applied to a case study in San Francisco Bay that shows the importance: of the redundancy of the road network, considering the accessibility of the Island that was prevented due to the collapse of the Bay Bridge, and of the interdependencies between the components of the physical infrastructure dimension, i.e. building system and road network.
Further research will be developed toward the insertion of other components of the physical infrastructure dimension (e.g. electricity grid, water supply, gas network, etc.) as well as the socio economic aspects.

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