Assessment of urban ecosystem resilience using the efficiency of hybrid social-physical complex networks

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One of the most important tasks of urban and hazard planning is to mitigate the damages and minimize the costs of the recovery process after catastrophic events. The rapidity and the efficiency of the recovery process are commonly referred to as resilience. Despite the problem of resilience quantification has received a lot of attention, a mathematical definition of the resilience of an urban community, which takes into account the social aspects of a urban environment, has not yet been identified. In this paper we provide and test a methodology for the assessment of urban resilience to catastrophic events which aims at bridging the gap between the engineering and the ecosystem approaches to resilience. We propose to model a urban system by means of different hybrid social-physical complex networks, obtained by enriching the urban street network with additional information about the social and physical constituents of a city, namely citizens, residential buildings and services. Then, we introduce a class of efficiency measures on these hybrid networks, inspired by the definition of global efficiency given in complex network theory, and we show that these measures can be effectively used to quantify the resilience of a urban system, by comparing their respective values before and after a catastrophic event and during the reconstruction process. As a case study, we consider simulated earthquakes in the city of Acerra, Italy, and we use these efficiency measures to compare the ability of different reconstruction strategies in restoring the original performance of the urban system.

Keywords: resilience, risk, street networks, complex networks

I. INTRODUCTION

Today more than 50% of humans around the world live in urbanised areas and this percentage is expected to increase by 2050 up to 86% in developed countries and up to 64% in developing countries. Consequently, the estimation of the resilience of urban systems against natural and human-induced risks, together with the implementation of successful strategies aiming at resilience strengthening and risk mitigation, represents a urgent challenge for the scientific community, with potential impact on billions of human lives.

Cities are among the most complicated and beautiful human artefacts, being the result of the intricate interaction of several constraints and processes which determine, reshape and refine the urban structure at all scales. One of the most relevant of such constraints is geographical: cities are embedded in a geometrical space, and their structure and development is heavily and undoubtedly affected — and to some extent driven — by the morphology of the surrounding environment. Then, there is a technological component, consisting of all the buildings and services provided by the city itself, together with the infrastructures that physically link them together: as a matter of fact, urban areas have become more attractive than rural settlements only because they guarantee a faster and more efficient access to a wider set of facilities, services and opportunities. Finally, and more importantly, there is the human aspect, i.e. all the citizens that reside, move and work within this physical frame, together with all the social, economical, cultural and historical processes that contribute to the evolution of an urban area over the centuries. Taking into account all these factors, we easily realise that a city can be effectively considered a complex system, i.e., according to one of the most general definition available, a system consisting of many interacting units with the ability to generate a non-trivial, collective behaviour through the combination of simple mechanisms acting at a local scale.

In the last few decades there has been an increasing interest for the quantitative study of urban systems
from a complex systems perspective, and several methods and metrics have been proposed to measure the structural properties of cities and to quantify their evolution over time (Wilson 1970; Bettay and Longley 1994; Batty 2007; Makse et al. 1995; Salingeras 2005; Marshall 2004; Bettencourt et al. 2007), with particular attention to the study of street patterns and transportation networks (Cardillo et al. 2006; Crucitti et al. 2006; Scala et al. 2006; Bettencourt and West 2010; Porta et al. 2011; Strano et al. 2012).

Despite recent literature has pointed out the necessity to introduce ad-hoc metrics to quantify the resilience of a city against shocks (Dalziell and McManus 2004), to date a unique and universally accepted definition of urban resilience is still missing. So far, the efforts to provide an operational measure to assess resilience of urban systems against shocks and disasters have been inspired by two main philosophies, namely the engineering vision and the ecosystem vision, which are fundamentally different in the spirit and, to some extent, diverging (Lorenz 2010).

In the engineering vision, the resilience of a city or a metropolitan area depends on the capability of all the physical components of the system, including buildings and transportation infrastructures, to absorb the damages due to an external shock and to quickly restore their state before the shock (O’Rourke 2007; Reed et al. 2009; Bruneau et al. 2003; Pimm 1984; Opricovic and Tzeng 2002).

In the ecosystem approach, instead, resilience is defined as the capability of the whole urban system to recover the full set of functionalities and services that existed before the shock, even without returning exactly to the state before the shock (Holling 1973; 1986; 2001; Holling and Gunderson 2002; Polke 2006; Kovalenko and Sornette 2013). This implies that, due to the restoration of the infrastructures and services damaged by the shock, the city might evolve in something slightly different from what it was before, while keeping its identity in a broader sense. On the one hand, the engineering approach explicitly requires that each single component of the system, due to the restoration process, reaches a new state in which its performance is not worse than one it had before the shock occurred. On the other hand, the ecosystem approach to resilience provides a more general framework to understand the recovery of complex systems (Holling 1996). However, this approach requires that the metrics employed to quantify resilience should be able to capture the performance of the system as a whole, which is usually much more than the algebraic sum of the performances of its single components. Determining which of the two approaches is more appropriate for the quantification of urban resilience is still a matter of active debate.

In this paper we engage with this debate by presenting a consistent framework for the quantification of urban systems resilience, which interpolates between the engineering and the ecosystem approach, allowing a quantitative estimation of system resilience while focusing, at the same time, on the performance of the urban system as a whole. This framework is based on the representation of cities as complex networks. In particular, we make use of Hybrid Social-Physical Networks (HSPNs), which provide a compact representation of the geographical, technological and social aspects of a city. Then, we propose a set of network efficiency indexes to quantify the performance of a HSPN. We show that the damage inflicted to a city by a shock can be easily quantified as the ratio between the efficiency of the corresponding HSPNs after and before the shock. Similarly, the effectiveness of different reconstruction strategies is compared by computing the evolution of the network efficiency of the HSPNs obtained using each strategy.

As a case study we considered the city of Acerra (Italy). We first constructed three HSPNs of Acerra in the pre-shock configuration. Then, we quantified the damage inflicted to the original networks by simulating earthquakes of increasing intensity. Finally, we compared the performance of six different reconstruction strategies in restoring the original HSPN efficiency. The results suggest that the weakness of the urban ecosystem of Acerra is due to an high-risk historical centre and that reconstruction strategies which allocate a large portion of displaced people in few distant points can not completely restore the pre-shock efficiency.

The paper is organised as follows. In Section II we briefly discuss the state of the art about urban resilience quantification, focusing on the theoretical contributions to the field recently provided by researchers in complexity and network science. In Section III we define three Hybrid Social-Physical Networks associated to a city and we propose a set of efficiency metrics to quantify their performance. In Section IV we define a measure to assess the resilience of a urban system based on the efficiency of the associated HSPNs, and we review a few reconstruction strategies typically employed in the aftermath of a disaster. In Section V we report the results of the proposed methodology on a case study, based on the simulation of earthquakes of increasing intensity in the city of Acerra (Italy), and we discuss the ability of different reconstruction strategies to recover the original performance of the city. Finally, in Section VI we report a discussion of the results and suggest some potential future extensions of this work.

II. MOTIVATION AND RELATED WORKS

The resilience of infrastructure and transportation systems against natural and human-induced disasters has been largely investigated in the literature and several methods to quantify resilience have been proposed, anal-
Complex network theory has also been successfully employed to quantify the resilience of urban systems. For instance, Reed et al. (2009) proposed a method to characterize the behavior of networked infrastructures prone to natural hazards, considering the interdependency of the system, with applications on power and telecommunication networks. Ouyang et al. (2012) proposed a multi-stage framework to analyse power transmission grids resilience and have identified, for each stage, a series of resilience-based improvement strategies. Maliszewski and Perringer (2012) hypothesized that the resilience of power distribution systems depends on two main factors, i.e., the environment where the network operates, and the priority policy employed during restoration. Attok-Okine et al. (2009) proposed a resilience index for urban infrastructures based on the Belief Function framework, while Li and Lence (2007) introduced a resilience index defined as the ratio between the failure probability and the recovery probability. Omer et al. (2009) focused on the resilience of telecommunication cable systems, defining it as the ratio between the amount of information transmitted after a disruption and the amount carried before the shock occurred. The reliability of infrastructure networks prone to natural hazards has been largely discussed in (Pinto et al., 2006), and several different methods based on connectivity and flow were recently analysed (Li and He, 2002; Dueñas Osorio and Rojo, 2011; Cavalieri et al., 2012; Franchin and Cavalieri, 2013a).

In a recent paper, Tamvakis and Xenidis (2013) provided a comparative review of several methods for resilience quantification, pointing out that most of the existing approaches might actually have quite limited applicability, due to the fact that these methods usually rely on some ad-hoc assumptions and often focus on specific subsystems, like telecommunication or power distribution networks. As a result, although some of the concepts and methodologies are interesting and potentially powerful, they cannot be straightforwardly extended to quantify the resilience of a urban system as a whole, which normally consist of several interconnected and interdependent subsystems.

In the last decade or so, important contributions to the problem of measuring the robustness of a system and quantifying its resilience to attacks and failures have come from the analytical study of complex networks. Complex network theory has proven to be a robust theoretical framework to study the topology of networked systems and has largely been employed for the characterization of a variety of phenomena occurring in systems composed by interconnected units, including many biological, technological and social networks (Strogatz, 2001; Newman, 2003; Boccaletti et al., 2006). Recently, complex network theory has also been successfully employed to quantify and model the topological aspects of spatial networks in general (Barthélemy, 2011) and of street networks in particular (Crucitti et al., 2006; Strano et al., 2012). The complex network approach to resilience is based on the analysis of an extremely simplified model—a graph—, representing the elementary components of the original system and the relations among them. The main assumption is that such a network model, despite discarding some specific details, is nevertheless able to capture the fundamental properties of the original system. This approach has been successfully employed to study the robustness and resilience of complex transportation networks, information networks and power distribution systems (Albert et al., 2000; Callaway et al., 2000; Cohen et al., 2000; Paul et al., 2004) and has recently been extended to the case of multi-layer and interdependent networks (Berche et al., 2009; Buldyrev et al., 2010; Satumtira and Dueñas Osorio, 2010; Vespignani, 2010; Gao et al., 2011a,b; Huang et al., 2013).

As a matter of fact, the functioning of the infrastructures and services of a urban area heavily rely on the existence of an underlying road network, and the efficiency of a city as a whole undoubtedly depends on the topological properties of its street pattern. In this respect, the street network is one of the most important aspects of a city, since its structure is intimately connected with the reachability of services and facilities and therefore with the overall quality of life perceived by the citizens. The quantitative analysis of urban street networks has shown that their topologies have complex structural properties (Cardillo et al., 2006; Scellato et al., 2006; Porta et al., 2011; Barthélemy, 2011), and recent works seem to confirm that the street network plays a central role in shaping the evolution of an urban area (Batty, 2007; Marshall, 2004; Bettencourt et al., 2007; Strano et al., 2012; Southworth and Ben-Joseph, 2003). Consequently, it would be tempting to define the resilience of a urban system in terms of the resilience of its street network.

However, a urban system is indeed the result of the intricate combination of several technological and social processes, and all its richness and complexity cannot be fully captured by the analysis of the underlying street network alone. A meaningful assessment of urban resilience to shocks should be focused on the real impact of the shock on the efficiency of a urban system as perceived by the citizens, and should therefore take into account other factors that concur to the perceived post-shock lack of performance, including population density, location of facilities, services availability and relocation strategies.

In the next Section we introduce a simplified representation of urban systems based on hybrid complex networks, which provides a consistent framework to integrate the structure of the urban street network and information about inhabitants, buildings and services.
III. MODELLING URBAN SYSTEMS BY MEANS OF HYBRID SOCIAL-PHYSICAL NETWORKS

The methodology for the assessment of urban resilience to shocks that we present here aims at bridging the gap between the engineering and the ecosystem approach to resilience. On the one hand, we identify a set of measures which allow to quantify, from an engineering point of view, the ability of a urban system to return to its pre-shock performance after a disaster. On the other hand, in the same spirit of the ecosystem vision, our measures are able to quantify the resilience of urban system even when, due to the post-shock restoration process, the urban system has attained a different configuration.

Here we first review some standard metrics for complex street networks analysis, and we then introduce Hybrid Social-Physical networks, together with metrics to quantify their overall efficiency.

A. Networks of urban street patterns

Generally, networks can conveniently be described by means of graphs consisting of a set of points $\mathcal{N}$, called nodes or vertices, and by a set $\mathcal{V}$ of edges connecting pairs of points. A graph with $N = |\mathcal{N}|$ nodes ($\mathcal{N} = \{n_1, n_2, n_3, \ldots n_N\}$) and $K = |\mathcal{V}|$ edges ($\mathcal{V} = \{v_1, v_2, v_3, \ldots v_K\}$) can be represented by giving its adjacency matrix, i.e. the $N \times N$ matrix $A = \{a_{ij}\}$ whose entry $a_{ij}$ is equal to 1 if there is an edge connecting node $i$ and node $j$, while $a_{ij} = 0$ otherwise. It is also possible to assign a weight or a length $l_{ij}$ to each edge linking nodes $i$ and $j$ in a graph, thus defining a weighted adjacency matrix $\{l_{ij}\}$.

Spatial networks are a special class of complex networks whose nodes are embedded in a space associated with a metric. Typical examples of spatial networks include electric power grids (Kinney et al., 2005) and transportation systems including rivers, trade routes and street networks (Crucitti et al., 2006; Strano et al., 2012; Pitts, 1965). In the case of street networks, each crossing is represented by a node while edges represent street segments, so that two nodes are connected by an edge if the corresponding crossings are adjacent to the same segment of road. Given a city, in the following we denote by $G(\mathcal{N}, \mathcal{V})$ the graph representing the urban street pattern, where $\mathcal{N}$ is set of street junctions and $\mathcal{V}$ is the set of street segments. Street networks are naturally embedded in a two-dimensional Euclidean space, whose metric is the usual Euclidean distance, so that the lengths $l_{ij}$ of the edges satisfy the triangular equality (Barthélemy, 2011).

In transportation and communication networks it is usually important to know how to move or send an information from a node $i$ to another node $j$. An alternate sequence of nodes and edges that starts from $i$ and ends in $j$ is called a walk from $i$ to $j$. If there exists a walk between node $i$ and node $j$, we say that $i$ and $j$ are connected. A maximal set of nodes which are mutually connected to each other is called a component of the graph.

If not all the pairs of nodes in the graph are connected, then the graph is composed by more than one component. Each walk is associated to a cost, that is the sum of the lengths of the edges involved in the walk. If each node of the walk is traversed only once, then the walk is called a path. The path from $i$ to $j$ having minimal length is called shortest path and its length is denoted by $d_{ij}$. If two nodes are not linked by any walk, then $d_{ij}$ is set to $\infty$, and the two nodes are said to be disconnected.

A measure of the typical separation between nodes in the graph is the characteristic path length $L$, that is the mean value of the length of the shortest paths between all the possible pairs of nodes:

$$L = \frac{1}{N(N-1)} \sum_{i,j \in \mathcal{N}, i \neq j} d_{ij}, \quad (1)$$

In general, lower the characteristic path length, the better the communication between any pair of nodes chosen at random. Using the characteristic path length to measure the resilience of a city is possible but indeed not convenient, since $L$ becomes infinite as soon as there exists at least one pair of disconnected nodes. However, the result of a shock event on a city, like an earthquake or a flood, is often a disconnected street network, which always has an infinite characteristic path length independently of the actual number of pairs of sites that remain disconnected after the event. The network efficiency, proposed in reference (Latora and Marchiori, 2001), is a measure which allows to overcome the subtleties due to infinite characteristic path lengths and can be therefore used to quantify the average reachability of the nodes even when the network is not connected, e.g. in the case of partially disrupted road networks after a disaster. The efficiency $e_{ij}$ of the communication between nodes $i$ and $j$ in a generic graph is defined as the inverse of the length of the shortest path connecting $i$ to $j$, i.e. $e_{ij} = \frac{1}{d_{ij}}$. The efficiency is minimal and equal to 0 when $i$ and $j$ are disconnected, i.e. when $d_{ij} = \infty$. In the case of spatial graphs, the efficiency of a pair of nodes is usually normalized dividing it by the Euclidean distance between the two nodes, so that the efficiency between $i$ and $j$ is defined as $e_{ij} = \frac{d_{ij}^{eucl}}{d_{ij}}$, where $d_{ij}^{eucl}$ is the Euclidean distance between node $i$ and node $j$. Notice that the resulting normalized efficiency is maximal and equal to 1 if and only if the shortest path between $i$ and $j$ runs exactly along the direction of the geodesic which connects them. The global efficiency of a spatial network is defined as the average of the normalized pairwise efficiency over all possible pairs of nodes (Vragović et al., 2005):

$$E = \frac{1}{N(N-1)} \sum_{i,j \in \mathcal{N}, i \neq j} \frac{d_{ij}^{eucl}}{d_{ij}}. \quad (2)$$
Notice that the global efficiency is normalized in $[0, 1]$, since in general the distance $d_{ij}$ between node $i$ and node $j$, which is measured as the total length to be traversed in order to get from $i$ to $j$ using a sequence of street segments, is larger than the Euclidean distance between $i$ and $j$, so that each term in the summation is $\leq 1$. Consequently, it is possible to compare in a consistent way the efficiencies of two distinct graphs $G$ and $G'$, even if they have a different number of nodes and edges.

### B. Construction of Hybrid Social-Physical Networks

The street network of a city is the main physical component of the hybrid network description of urban systems that we propose. In order to take into account some of the social aspects of a city, we enrich the road network adding different kinds of nodes, which represent citizens, buildings and facilities, and different kinds of links, which model the relationships between social and physical elements. We call the resulting graph a Hybrid Social-Physical Network (HSPN). The idea of modelling cities by constructing augmented graph models which integrate information about their main components has recently been employed in the field of resilience assessment (see for instance Cavalieri et al. (2012); Franchin and Cavalieri (2013a)).

According to the nature and accuracy of the information used to augment the road network, we can actually obtain several different HSPN representations of a urban system. A first example is the residential HSPN, which includes information about population and building locations and is constructed as follows. For each building we add a new building node, whose coordinates are those of the centroid of the building footprint on the map. Then, each building node is connected to the road network by means of a new doorstep edge orthogonal to the street segment closest to the building. The other endpoint of a doorstep edge, called a doorstep node, is chosen to be either one of the existing crossings in the street network or a newly ad-hoc added node.\(^1\)

The construction of the residential network is illustrated in Figure 1. In this case the HSPN consists of two sets of nodes and two set of edges, namely

- The set of intersection nodes, which we called $\mathcal{N}$.
- The set of building nodes, hereafter referred as $\mathcal{B}$.
- The set of street segments, which we called $\mathcal{V}$.

\(^1\) The choice of doorstep nodes was made by hand in order to guarantee, at the same time, that the direction of doorstep edges remains as close as possible to the direction orthogonal to the closest street segment and that only a small number of extra nodes were actually added to the existing road network.

FIG. 1: Network representation of a city. Each building is associated to a new node and is connected to the road networks by means of a doorstep edge incident on a doorstep node. Also, each citizen living in a building is represented as a virtual (green) node attached to the building. The distance between two citizens living in buildings incident on the same doorstep node is set to zero.

- The set of doorstep edges, denoted by $\mathcal{V}_D$

With a little abuse of notation, we include in the set $\mathcal{N}$ the doorstep nodes, besides some of them were not initially present in the road network and have been added to the street network just to attach doorstep edges. The street network augmented with the set of building nodes and doorstep edges is denoted by $\mathcal{G}_B(\mathcal{N} \cup \mathcal{B}, \mathcal{V} \cup \mathcal{V}_D)$. In order to correctly take into account the mutual reachability of citizens, each building is also attached to a set of citizen nodes. These are just virtual nodes introduced to model the relationships between citizens and the buildings in which they live. By definition, the distance between two citizen nodes is equal to the distance, on the road network, between the doorstep nodes of the buildings in which they live. Consequently, if two citizen nodes are attached to the same building or to two separate buildings incident on the same doorstep node then their distance is set to zero. This is clarified by Figure 1. Both the social and the physical part of the HSPN can be even more complex, and a procedure similar to that used to construct residential HSPNs can be employed to augment the street network with additional information. For instance, if we consider the street network together with residential and commercial buildings, we can assess the capability of citizens to reach goods supplies. The corresponding graph is denoted by $\mathcal{G}_G(\mathcal{N} \cup \mathcal{B} \cup \mathcal{G}, \mathcal{V} \cup \mathcal{V}_B \cup \mathcal{V}_G)$, where $\mathcal{G}$ is the set of nodes representing commercial buildings and $\mathcal{V}_G$ is the set of logical links connecting this commercial buildings with the adjacent street segments. We call this graph a goods HSPN. In order to quantify its relative importance, we associate to each goods building $i$ a weight $G_i$, which is
proportional to the amount of goods it makes available to citizens.

Similarly, we can also construct a service HSPN to assess the capability of citizens to access public services, like schools, hospitals and other public infrastructures. In this case the HSPN is denoted by \( G_S(\mathcal{N} \cup \mathcal{B} \cup \mathcal{S}, \mathcal{V} \cup \mathcal{V}_B \cup \mathcal{V}_S) \), where \( \mathcal{S} \) is the set of nodes representing public buildings and \( \mathcal{V}_S \) is the set of logical links connecting public buildings to intersection nodes. As in the case of goods HSPN, the relative importance of a service \( i \) in terms of quantity and/or quality of service provided to citizens is encoded in a weight \( S_i \).

We notice that this methodology allows to construct many other HSPNs corresponding to different lifelines. For instance, information about the electric grid network and the water supply/sewage network can be included in the model, to investigate the capability of the urban system to provide citizens with electricity and water, respectively.

The potential of this approach lays in the fact that the global performance of the HSPN associated to a given service can be considered as a proxy of the accessibility of that service by the citizens, i.e. as a measure of the quality of the service provided. Thus, it is possible to quantify and compare the performance of the HSPN in distinct configurations of the physical networks, even if some infrastructures are not present in one of the configurations. By performing this analysis before and after the reconstruction which follows an hazardous event, which damages some of the pre-existent physical components of the urban system, we can quantify how the quality of public services provided to citizens has been affected, although the physical systems are rebuilt and rearranged in a new configuration. Thus, we believe that the HSPN approach is an effective methodology to provide a quantitative assessment of the resilience of a urban system —as requested by the engineering approach— based on a systemic perspective that properly takes into account the social aspects of the system and the perceived efficiency of the city as a whole —as indicated by the ecosystem approach.

### C. Efficiency of Hybrid Social-Physical Networks

We define here some efficiency metrics for HSPNs which are inspired by the normalized global network efficiency given in equation (2). The mere definition (2) is inadequate to estimate the efficiency of the city, because it does not take into account the number of people living in each building. We can then devise a measure of efficiency of communications between people inside buildings by summing over all couples of inhabitants and using \( d_{ij}^{eucl} / d_{ij} = 1 \) for couples of inhabitants living at distance zero, i.e. assuming the maximum efficiency in their communications. In the same spirit of Equation (2), we define the efficiency of a residential HSPN as:

\[
E_{oc} = \frac{1}{H_{tot}(H_{tot} - 1)} \sum_{i \in \mathcal{B}} H_i \left( (h_i - 1) + \sum_{j \in \mathcal{B}, j \neq i} H_j d_{ij}^{eucl} d_{ij} \right)
\]

\[
= \frac{1}{H_{tot}(H_{tot} - 1)} \sum_{i \in \mathcal{B}} H_i \left( (h_i - 1) + \sum_{j \in \mathcal{B} \setminus \{i\}} H_j d_{ij}^{eucl} d_{ij} \right),
\]

where \( i, j \) are the indexes of nodes representing buildings, \( H_{tot} \) is the total number of inhabitants of the city, \( H_i \) is the number of people living in building \( i \), \( \mathcal{B} \) is the set of nodes representing buildings, \( d_{ij} \) is the length of the shortest path between \( i \) and \( j \) evaluated on graph \( G_S \) and \( h_i \) is the number of inhabitants that live in the set \( \mathcal{I} \) of buildings with zero distance to building \( i \). This definition of efficiency for a residential HSPN, is indeed able to quantify the mutual reachability of people living in the city. In fact, the lower the distance among people in the augmented network, the higher the efficiency value of the corresponding HSPN, and vice-versa. Notice that in the summation over \( j, j \neq i \) we set \( d_{ij}^{eucl} d_{ij} = 1 \) for couples of buildings at zero distance. The term \( (h_i - 1) \) inside the parentheses, multiplied by \( H_i \), takes into account the couples of inhabitants that live in the same building and whose efficiency is \( e_{ii} = 1 \).

It is possible to define an efficiency also for goods HSPNs, by substituting the outer summation in Equation (3) with a summation over the set \( \mathcal{G} \) of the buildings that contain goods, e.g. shops and retail stores, and dividing by the quantity \( G_{tot} \) which is equal to the sum of the importance of all goods buildings. In formula:

\[
E_{cg} = \frac{1}{G_{tot} H_{tot}} \sum_{i \in \mathcal{G}} \sum_{j \in \mathcal{B}} G_i H_j d_{ij}^{eucl} d_{ij}
\]

\[
= \frac{1}{G_{tot} H_{tot}} \sum_{i \in \mathcal{G}} G_i \left( h_i + \sum_{j \in \mathcal{B} \setminus \{i\}} H_j d_{ij}^{eucl} d_{ij} \right),
\]

where \( G_i \) is an estimate of the amount of goods in the shop \( i \in \mathcal{G} \), \( d_{ij} \) is the length of the shortest path between \( i \) and \( j \) evaluated on the graph \( G_S \). Notice that Equation (4) measures the average of the inverse of the normalized distance between people and goods sold in shops, and effectively quantifies how easily citizens can access goods supplies.

Similarly, the efficiency of the service HSPN is given

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2 Notice that the distance between two buildings is set to zero if their corresponding doorstep edges coincide on the same doorstep node.
by the equation:

\[
E_{cs} = \frac{1}{S_{tot}H_{tot}} \sum_{i \in S} \sum_{j \in B} S_i H_j d_{ij}^{eucl} d_{ij} \nonumber
\]

\[
= \frac{1}{S_{tot}H_{tot}} \sum_{i \in S} \left( h_i + \sum_{j \in (B \setminus I)} H_j d_{ij}^{eucl} \right),
\]

which is just the average of the inverse of the normalized distances between people and services. In this case, \( S_i \) represents a measure of the importance of the service \( i \) (e.g. the floor area of the building or the total number of citizens that can potentially use the service), \( S \) is the set of nodes representing service buildings and \( S_{tot} = \sum_i S_i \). In this equation the length \( d_{ij} \) of a shortest path is evaluated on the graph \( G \in S \).

**IV. USING HSPNS TO QUANTIFY URBAN RESILIENCE**

The main idea in this paper is to use the efficiency measures on HSPNs to quantify the resilience of a urban system, by comparing their respective values before and after a catastrophic event and during the subsequent restoration. In this section we first report the classical definition of resilience and introduce an ad-hoc normalization. We then review six reconstruction strategies which permit to simulate and trace the restoration process.

**A. Measures of resilience**

The classical approach to urban resilience is based on the definition of a recovery function \( Y(t) \), whose value at time \( t \) is equal to the measured performance of the system at that time. If the recovery process starts at time \( t_1 \) and is completed at time \( t_2 \), then the resilience \( R \) of the urban system is defined as the area under the recovery curve \( \text{Reed et al., 2009} \)

\[
R = \int_{t_1}^{t_2} Y(t) dt. \tag{6}
\]

Notice that \( R \) depends both on the time required by the recovery process and on the reconstruction strategy adopted. By using the HSPN model of a city, it is possible to define the performance of the urban system at time \( t \) as the ratio between the efficiency \( E(t) \) of the associated HSPN at time \( t \) and the efficiency \( E_0 \) of the HSPN just before the disaster occurred, namely

\[
Y(t) = \frac{E(t)}{E_0}. \tag{7}
\]

This definition of performance requires to know the structure of the HSPN at each time during reconstruction. However, this information depends on several factors including the available budget and the promptness of the reconstruction, and is usually not easy to obtain. Consequently, we remove any explicit dependence of the resilience on time, and use a recovery function \( Y(C) = E(C)/E_0 \) defined as the ratio between the efficiency \( E(C) \) of the urban system when \( C \) citizens have been relocated and the efficiency \( E_0 \) immediately after the disaster. In particular, we make use of the normalized performance:

\[
y(C) = \frac{Y(C) - Y(0)}{1 - Y(0)}. \tag{8}
\]

Notice that \( y(C) = 0 \) in the aftermath of the disaster, i.e. when \( y(C) = 1 \) when \( Y(C) = 1 \). In order to quantify the resilience of a urban system we define the measure:

\[
\mathcal{R} = \int_0^{C_{\max}} y(C) dC \nonumber
\]

\[
\frac{C_{\max}}{C_{\max}}, \tag{9}
\]

where \( C_{\max} \) is the total number of people to be relocated after a certain event. In the following we employ Equation (9) instead of the classical definition of resilience given in Equation (6), as it permits to appreciate the recovery of a city closely after the disaster and to compare different strategies of reconstruction after events of different magnitude. To date, a discussion about a proper way to compute a normalized resilience is ongoing (Franchin and Cavalieri, 2013b).

**B. Reconstruction strategies**

We review here the six reconstruction strategies considered in the case study reported in Section V.

The first strategy, referred to as status quo down-up, aims at re-obtaining exactly the same configuration of buildings and services that the city had before the catastrophic event occurred. The reconstruction process is discretized into \( n \) steps. In each step a fraction \( 1/n \) of the displaced citizens (those living in the damaged buildings) is reallocated, assuming that the buildings are restored starting from the smallest ones and proceeding towards the largest ones, i.e. from the cheapest to the most expensive. Blocked roads are recovered when the buildings that caused their interruption are made safe or reconstructed. In the second strategy, referred to as status quo up-down, the city eventually returns to the undamaged configuration, as in the status quo down-up, but the restoration process starts with the largest buildings and proceeds towards the smallest ones.

The third strategy, hereafter referred to as new sites down-up, consists in reallocating part of the displaced citizens in new residential sites. Also this process is discretized into steps. In the first step some new buildings
are constructed in 4 empty areas (highlighted in figure 9), to reallocate 20% of the displaced citizens. Then the existing buildings are restored as in the first strategy, from the smallest to the largest ones, until all citizens have been reallocated. Notice that in the new sites down-up strategy some of the existing buildings are not ever recovered, since part of the population is reallocated in the newly constructed buildings. To re-establish the original urban street pattern, it has been assumed that the interrupted roads, that would have not been recovered (since interrupted by buildings that are not recovered), are re-established during the last step. The fourth strategy, called new sites up-down, is similar to the new sites down-up one, but, after reallocating the first 20% of citizens in the newly constructed buildings, the restoration of damaged buildings proceeds from the largest to the smallest ones. The new sites strategies are adopted in real cases to recover basic urban functionalities as fast as possible, and have been recently employed in the aftermath of earthquakes, e.g. in the case of L’Aquila 2009 earthquake, in Italy (Cosenza and Manfredi 2010).

The fifth strategy, called status quo inwards, consists in rebuilding the city as in its undamaged configuration, moving from the suburbs to the centre. Finally, the status quo outwards is similar to status quo inwards but the reconstruction starts from the centre of the city and proceeds toward the suburbs.

V. A CASE STUDY: THE CITY OF ACERRA

As a case study to test our methodology for resilience quantification we considered a urban area —the city of Acerra, in Italy— and we simulated several earthquake scenarios, evaluating the damage caused by each earthquake and the ability of different reconstruction strategies in restoring the pristine performance of the urban system, measured in terms of the efficiency of the corresponding residential, goods and services HSPN.

Acerra is a medium-sized city in the Province of Naples, in Italy, about 20km north-east of Naples (Figure 2); its foundation dates back to as early as 400 BC, which makes it one of the oldest cities in that region. The urban configuration, typical of many other medium-sized cities in Italy, is characterised by a dense historical centre, where most of the buildings are ancient masonry buildings, surrounded by more recent urban expansion areas, mainly consisting of reinforced concrete buildings; the built-up area is surrounded by a countryside area, where a large industrial settlement is also located. The whole territory extends over a surface of about 54km\(^2\) and its population is estimated in about 55,000 inhabitants. Acerra is prone to seismic risk, due to its closeness to the seismogenic areas of the Appennines, which are just about one hundred kilometres away from the city center. Figure 3 reports the seismic hazard in terms of annual rate of occurrence of events with a Peak Ground Acceleration (PGA) larger than a certain value. Furthermore, the city is exposed to flood risk, due to the Regi Lagni river which borders the built-up area, and to industrial risk, due to the infrastructures and factories located in the industrial area around Acerra. In the following we will focus on seismic risk alone.
A. Numerical simulations

In order to study the resilience of Acerra, we extracted detailed information about the street network organisation, location of buildings and building typology. Then, we constructed three different HSPNs (namely, a residential HSPN, a goods HSPN and a service HSPN where the set of services was restricted to schools), and we simulated earthquake scenarios corresponding to increasing PGA values. By integrating this information with an ad-hoc fragility model, we simulated building failures due to each earthquake and then we analysed the subsequent reconstruction process, by comparing the performance of six different reconstruction strategies. We provide here the details of the simulations, and we discuss afterwards the results.

**Data acquisition.** We used GIS software to collect and integrate information about the street network and the location and typology of buildings in Acerra. We divided buildings into structural typologies and we measured the total floor area of each typology, which was later used to estimate the number of citizens living in each residential building and the relative importance of retail shops and services. In Figure 4 we show the street network of Acerra, in which the positions of buildings are reported as black squares.

**Fragility model.** We employed an ad-hoc model to estimate the probability that each building will be damaged by an earthquake of a certain intensity and the probability that a damaged building would also interrupt the transit along the streets to which it is adjacent. Concerning building damage, we modelled the probability that the building would exceed the “onset of damage” (and thus would be considered unfit for occupation or use) due to an earthquake of PGA equal to $x$ through a log-normal distribution function:

$$P_b(x; \mu, \sigma) = \Phi \left( -\frac{\ln x - \mu}{\sigma} \right). \quad (10)$$

The parameters $(\mu, \sigma)$ have been set equal to $(-1.03, 0.35)$ for masonry buildings and equal to $(-0.91, 0.29)$ for reinforced concrete buildings, according to reference (Ahmad et al. 2011). Notice that the adopted fragility model does not consider building height as a parameter and does not take into account failure correlation.

If a building is over the onset of damage, then its failure could also make inaccessible the streets adjacent to it, either because of building debris fallen on the road or because of access restrictions imposed for safety reasons. This road interruption probability is defined as:

$$P_r(h, l) = \begin{cases} 1 & \text{if } h \geq l, \\ \frac{l}{h} & \text{otherwise}, \end{cases} \quad (11)$$

where $h$ is the height of the building and $l$ is the width of the road. Notice that the higher the building and the narrower an adjacent road, the higher the probability for that road to be made inaccessible if the building is over the onset of damage. If a street segment is inaccessible, it is removed from the street network. In general, the removal of street segments has negative effects on the overall reachability of the street network (and of the HSPN obtained from the same network), and could also cause the fragmentation of the street network into several isolated components, separated from each other.

**HSPN parameters.** The definitions of efficiency for residential, goods and service HSPNs given in Equations (3), (4) and (5), depend on the quantification of the number of citizens living in each residential building ($H_i$ and $h_i$) and of the relative importance of stores ($G_i$) and service buildings ($S_i$). The number of inhabitants of residential buildings was estimated by considering the average density of inhabitants per square meter, obtained by dividing the total number of citizens in Acerra (i.e., 55,000) by the total number of square meters in residential buildings. This yields a value of one inhabitant per 30 square meters. Concerning the goods HSPN, we considered the total area of each store as a proxy of its importance. Finally, we considered services HSPN restricted to schools and students, and we considered the total area of a school as a proxy for its relative importance $S_i$.

**Earthquake simulation.** We employed Monte Carlo techniques to simulate several earthquakes scenarios corresponding to increasing PGA values. In each scenario, we computed the probability for each building of being beyond the onset of damage (according to Equation (10)), and the corresponding probability for roads to be made inaccessible by damaged buildings (according to Equation (11)). This resulted, for each realisation, in a certain number of citizens to be relocated because of the damage inflicted by the earthquake to residential buildings, and to a set of street segments to be removed from the road network and from the HSPNs since they were made unusable by damaged buildings, respectively. For each simulated scenario we constructed the corresponding residential, goods and schools HSPNs, and we evaluated the damage inflicted to the urban system as the difference between the efficiency of the HSPN before the simulated earthquake and the efficiency of HSPNs right after the earthquake occurred.

**Recovery simulation.** For each earthquake scenario, we simulated the six different reconstruction strategies detailed in Section IV.B. During reconstruction, buildings were progressively put back in place, citizens were relocated and damaged street segments restored. We used Equation (8) as a recovery function and Equation (9) to compare the recovery of the urban system due to the implementation of different strategies.
FIG. 4: Buildings (black points) and street patterns (bold lines) network for the city of Acerra.

B. Results

We considered several earthquake scenarios, corresponding to PGA values in the range $[0.05g, 1.0g]$, and we evaluated three sets of measures for each scenario, comparing their values with the undamaged configuration. In particular, we computed:

1. The number of undamaged buildings and the number of not displaced people as a function of PGA, whose values are reported in figure 5.

2. The values of $E_{cc}$, $E_{cg}$ and $E_{cs}$ corresponding, respectively, to residential, goods and schools HSPN. The results are reported in Figure 6.

3. Several metrics to quantify the performance of the damaged street network, including the number of connected components, the number $S$ of nodes in the largest component and the characteristic path length $L$ of the largest connected component. The results are reported in Fig. 7.

Notice that all the results shown in Fig. 5, 6 and 7 are normalised with respect to the initial (undamaged) configuration. The absolute values corresponding to the initial configuration are reported in Table I.

Figure 5 suggests that the number of undamaged buildings and the number of not displaced people have the same exponential decay with PGA, and that the corresponding exponent value is $b \simeq -4$. This high correlation between undamaged buildings and not displaced people is mostly due to the fact that we assumed a constant value for the number of inhabitants per square meter. Also, we could have expected a different decay exponent if we had considered that people could have also been displaced from undamaged buildings, e.g. because of unavailability of basic support services ([Cavaleri et al.], 2012). We observe a faster exponential decay, with exponent $b \simeq -9$, for $E_{cc}$, $E_{cg}$ and $E_{cs}$ for values of PGA between 0.25g and 0.6g, as shown in Figure 8. These results confirm that the efficiency of HSPNs can be reliably used as a proxy of the quality of a urban system.

Furthermore, from Figure 7 we note that the behaviour of the street network is consistent with a percolation transition, indicating the existence of a critical PGA range around 0.25g beyond which the street network is broken into many parts and does not exhibit a giant connected component any more ([Stauffer and Aharony], 1994; [Dorogovtsev et al.], 2001). This is due to the fragility functions adopted to simulate building damage, which have a significant increase in the collapse probability for values of PGA in the range $[0.20g, 0.30g]$. It is also evident from Figure 7 that the relative characteristic path length has a peak corresponding to PGA=0.25g. We believe that this abrupt increase is due to the failure of most short-cut roads. Although we cannot claim that the critical PGA value for the percolation transition is exactly at PGA= 0.25 (a correct estimation of this threshold would require more fine-grained calculations), we notice that such a value of PGA would most probably damage the majority of the masonry buildings, which are placed in

### Table I: Characteristics of the undamaged configuration.

| Measure          | Value |
|------------------|-------|
| $E_{cc}$         | 0.746 |
| $E_{cg}$         | 0.252 |
| $E_{cs}$         | 0.313 |
| undamaged buildings | 3493  |
| not displaced citizens | 55000 |
| Number of connected components | 1 |
| Characteristic path length (m) | $L(0) = 1798$ |
| Nodes belonging to the largest component | $S(0) = 4638$ |
The values $E_{cc}$, $E_{cg}$ and $E_{cs}$ divided by the original efficiency in the pre-shock networks as a function of PGA.

the center of Acerra, and would consequently fragment the city into a large number of small connected components. Therefore, it is actually the high density of masonry buildings located in the city center which causes the sudden fragmentation of the street network.

For the comparative analysis of the six reconstruction strategies we considered only three values of PGA, namely 0.2g, 0.25g and 0.3g, which are consistent with the most likely earthquake intensity in the region of Acerra. In Figure 8 we report a typical configuration of the simulated damaged network for each of the three values of PGA. During recovery, we measured the performance of the urban system by means of the efficiency of the HSPN. The typical plots of $E_{cc}$, $E_{cg}$ and $E_{cs}$ of one realisation corresponding to each value of PGA are reported in Figure 9, 11 and 12.

The values $\langle R \rangle$, averaged over several realisations of the three PGA scenarios, are reported in Table 11 along with the corresponding standard deviations $\sigma_R$. The table suggests some remarks about the ability of different reconstruction strategies to recover the pristine urban efficiency. First of all we observe that the new sites strategies provide quite slow efficiency recovery, if compared with the status quo strategies. In particular, in the new sites strategies after the first step, consisting in the reallocation of the 20% of the inhabitants into new buildings (the location of the four areas chosen for the simulated construction of those four new buildings are shown in Figure 9), the efficiency values always show a negligible increase. Furthermore, at the last step the efficiency values are not totally recovered to their initial values. This means that the new configuration of the city, with 4 new buildings used to reallocate the 20% of the displaced citizens, is less efficient than its original configuration. Also, it was not possible to detect any sensible difference between new sites up-down and new sites down-up.

We notice that for earthquakes of PGA = 0.2g and PGA = 0.25g, the status quo strategies (and in particular the status quo inward) guarantee the fastest recovery of $E_{cc}$ among all the reconstruction strategies considered.

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4 According to Figure 3, values of PGA larger than 0.3 are very unlikely to occur.
FIG. 8: Configuration of the simulated damaged physical network after simulated earthquake scenarios of PGA 0.2\textit{g} (a), 0.2\textit{g}(b) and 0.3\textit{g}(c).

This result can be explained by the fact that, in this particular case study, the masonry buildings, which are the most vulnerable to earthquakes, are mostly placed in the centre of the city. Hence, in the post-earthquake configuration the center of the city will remain much more disconnected, and in fact it is characterised by a considerably large “hole” at the center of the HSPN networks (as shown for instance in Figure 8). Thus, in the \textit{status quo outwards} strategy the first steps are not so efficient since the buildings are restored onto a seriously damaged network. Conversely, in the \textit{status quo inwards} strategy, the restored buildings are progressively reinstalled onto a network which is also progressively reconnected, making this strategy more resilient.

We would like to stress that the evaluation of the \textit{status quo inwards} strategy is of particular interest. In fact, in many old cities the center consists mainly of ancient masonry structural aggregates, and its reconstruction is particularly costly, both for technical issues and for conservation constraints. For these reasons, reconstruction of damaged historical cities is often more rapid in the suburbs than in the center.
| HSPN | PGA(g) | reconstruction strategy | \(\langle R \rangle\) | \(\sigma_R\) |
|------|--------|------------------------|----------------|--------|
| cc 0.2 | status quo outwards | 0.47391 | 0.08879 |
| * cc 0.2 | status quo inwards | 0.55236 | 0.09428 |
| † cc 0.2 | new sites up-down | 0.36180 | 0.09428 |
| ‡ cc 0.2 | new sites down-up | 0.38107 | 0.08869 |
| cc 0.2 | status quo up-down | 0.49051 | 0.08001 |
| cc 0.25 | status quo outwards | 0.42057 | 0.08230 |
| * cc 0.25 | status quo inwards | 0.56707 | 0.08151 |
| † cc 0.25 | new sites up-down | 0.33861 | 0.08539 |
| ‡ cc 0.25 | new sites down-up | 0.29228 | 0.09030 |
| cc 0.25 | status quo up-down | 0.48078 | 0.09865 |
| cc 0.25 | status quo down-up | 0.49351 | 0.08014 |
| cc 0.3 | status quo outwards | 0.43969 | 0.08190 |
| cc 0.3 | status quo inwards | 0.41964 | 0.08441 |
| † cc 0.3 | new sites up-down | 0.28566 | 0.09987 |
| † cc 0.3 | new sites down-up | 0.25792 | 0.09762 |
| cc 0.3 | status quo up-down | 0.45144 | 0.08706 |
| * cc 0.3 | status quo down-up | 0.45853 | 0.09530 |
| cg 0.2 | status quo outwards | 0.49691 | 0.08089 |
| cg 0.2 | status quo inwards | 0.52764 | 0.09833 |
| † cg 0.2 | new sites up-down | 0.48297 | 0.08193 |
| † cg 0.2 | new sites down-up | 0.26874 | 0.08987 |
| * cg 0.2 | status quo up-down | 0.63748 | 0.09920 |
| cg 0.2 | status quo down-up | 0.40420 | 0.09003 |
| cg 0.25 | status quo outwards | 0.41859 | 0.08798 |
| * cg 0.25 | status quo inwards | 0.57646 | 0.08102 |
| † cg 0.25 | new sites up-down | 0.36596 | 0.08714 |
| † cg 0.25 | new sites down-up | 0.24454 | 0.08885 |
| cg 0.25 | status quo up-down | 0.53955 | 0.08797 |
| cg 0.25 | status quo down-up | 0.43379 | 0.09598 |
| cg 0.3 | status quo outwards | 0.44838 | 0.08595 |
| cg 0.3 | status quo inwards | 0.43294 | 0.08732 |
| † cg 0.3 | new sites up-down | 0.32794 | 0.08493 |
| † cg 0.3 | new sites down-up | 0.18873 | 0.08525 |
| * cg 0.3 | status quo up-down | 0.51809 | 0.09438 |
| cg 0.3 | status quo down-up | 0.36390 | 0.09503 |
| cs 0.2 | status quo outwards | 0.48476 | 0.08221 |
| cs 0.2 | status quo inwards | 0.56003 | 0.09898 |
| † cs 0.2 | new sites up-down | 0.47966 | 0.08680 |
| † cs 0.2 | new sites down-up | 0.31011 | 0.09207 |
| * cs 0.2 | status quo up-down | 0.61563 | 0.08768 |
| cs 0.25 | status quo outwards | 0.45244 | 0.09527 |
| cs 0.25 | status quo inwards | 0.49339 | 0.09459 |
| † cs 0.25 | new sites up-down | 0.34012 | 0.08884 |
| † cs 0.25 | new sites down-up | 0.21159 | 0.09018 |
| * cs 0.25 | status quo up-down | 0.49917 | 0.09161 |
| cs 0.25 | status quo down-up | 0.43433 | 0.08902 |
| * cs 0.3 | status quo outwards | 0.50632 | 0.08900 |
| cs 0.3 | status quo inwards | 0.41086 | 0.09551 |
| † cs 0.3 | new sites up-down | 0.27636 | 0.08425 |
| † cs 0.3 | new sites down-up | 0.30121 | 0.08320 |
| cs 0.3 | status quo up-down | 0.44357 | 0.08407 |
| cs 0.3 | status quo down-up | 0.46652 | 0.08789 |

**FIG. 9:** The position of the new residential areas (circles) chosen for the new sites recovery strategies.
FIG. 10: The value of the efficiency $E_{cc}(C)$ of the residential HSPN as a function of the number of relocated people $C$ for the 6 recovery strategies in the 0.2g PGA(a), 0.25g PGA (b) and 0.3g PGA(c) earthquake scenarios. Each panel shows the absolute values of efficiency divided by the corresponding pre-shock efficiency $E_{cc}(0)$.

FIG. 11: Values of $E_{cg}(C)$ for the 6 recovery strategies in the 0.2g PGA(a), 0.25g PGA (b) and 0.3g PGA(c) earthquake scenarios, as a function of $C$. As for Figure 10, each panel reports the value of $E_{cg}$ at a certain reconstruction strategy divided by the efficiency of the original urban configuration.
FIG. 12: $E_{cs}$ as a function of $C$ for the 6 recovery strategies in the 0.2g PGA (a), 0.25g PGA (b) and 0.3g PGA (c) earthquake scenarios. The absolute values are normalized with the pre-shock efficiency $E_{cs}(0)$.
VI. CONCLUSIONS

In this paper we proposed a novel methodology to quantify the resilience of complex social-physical urban systems against disasters. This methodology aims to bridge the gap between the two classical approaches to resilience: the engineering resilience, generally meant as the capability of a system to recover its initial configuration after a shock, and the ecosystem resilience, generally meant as the capability of a system to recover its functionality even by reaching a new configuration. The procedure presented here is inspired by the idea that city resilience should properly take into account its social components, namely the citizens, which are the final users of the urban system as a whole. Our approach to quantify city resilience is based on the efficiency of hybrid networks composed by citizens and urban infrastructures.

In order to assess the capability of a city to recover its functionality after a shock event, we compared the efficiency of the corresponding hybrid networks before and after the shock event has occurred and, as a case study, we considered the city of Acerra, for which we simulated several earthquake scenarios and analysed residential, goods and schools hybrid social-physical networks. We also compared the ability of six different reconstruction strategies, which differ from each other for the assignment of reconstruction priorities, in restoring the pristine performance of the urban system.

While the main idea of the proposed methodology is to assess the resilience of urban recovery, the quantification of the efficiency of hybrid networks can be employed also for other purposes, e.g. to compare the efficiency of different urban configurations or different urban planning strategies (this would be a urban planning task), or to design the reconstruction operations after an hazardous event. Thanks to our approach, the best reconstruction strategy can be selected by identifying the physical configuration which maximises the performances of all the hybrid networks.

According to our metrics, the best strategy classes with respect to residential reallocation are the down-up and inwards. In fact these strategies provide a faster response in the immediate aftermath, securing and restoring many buildings in the first reconstruction step. In particular the status-quo strategies ensure the total recovery up to the original HSPN efficiency. The others strategies, allocating many citizens in a few distant new areas produce longer average distance between people and, consequently, a lower HSPN efficiency. We can then infer that a good reconstruction strategy should take care first of the restoration of the bulk of a city. The analysis of the street network fragmentation also underlines the weakness of the urban ecosystem of Acerra, in which the overall connectivity of the HSPNs heavily depends on the connectivity of a high-risk historical centre, consisting of ancient masonry buildings which are indeed more prone to seismic risk.

We would like to stress that these results are strongly related with the specific city configuration under study, and that extra care should be taken while trying to generalize these results to other specific cases. We also notice that the methodology we proposed in this work to quantify resilience is based only on the number of reallocated citizens, and does not account for the availability of financial resources, restoration rates or restoration prioritization, also considering emergency management issues. We believe that an estimation of resilience based on the actual restoration time, i.e. on the total time needed to restore the damaged buildings and to reallocate all the citizens, would be possible by introducing in the model additional information about financial resources and restoration rates. We also notice that the availability of financial resources and the prioritization strategies resulting from emergency management issues are indeed a social-economic background input, not depending on the adopted recovery strategy.

Once the financial aspect is introduced in the model, the methodology could also be enriched and refined by considering the different restoration costs associated to different building typologies. As a matter of fact, is estimated that the cost of rehabilitating masonry buildings in the historical centre, in Italy, is twice as larger than the cost of rebuilding reinforced concrete structures in a similar damage state, while the construction time in the first case is also significantly higher than in the second. This difference in restoration costs would affect the performance of the outwards strategies that start by rehabilitating the historical centre, and would therefore be substantially less effective than the inwards strategies. This observation could become even more important in the case of large scale disasters, where such strategies would require to invest a large amount of resources in the immediate aftermath of the disaster.

Further research activities on this topic are currently ongoing. In particular, a research direction of interest is the quantification of the impact of disasters on interconnected networks, by using some recent theoretical results about the fragility of complex interdependent networks (Cohen et al., 2000; Paul et al., 2004; Buldyrev et al., 2010; Gao et al., 2011a; Cohen et al., 2001). Another possible direction to explore is the usage of multiplex and multi-layer networks, which have been recently proposed as a valuable tool to model systems which consist of several different and intrinsically interdependent systems (Morris and Barthelemy, 2012; Brummitt et al., 2012).

The authors are currently working to enrich and calibrate the measures defined in this paper in order to propose a consistent set of quantifiable efficiency measures to estimate the quality of life perceived by the inhabitants of a urban systems, which could be used also to measure the resilience of cities in an ecosystemic and social-centric
REFERENCES

UN. Urban population, development and the environment 2011. Technical report, UN Population Division, 2010. URL http://www.un.org/esa/population/publications/urbanization/

UN. World urbanization prospects: The 2007 revision. Technical report, UN Population Division, 2008. URL www.un.org/esa/population/publications/events/

Yaneer Bar-Yam. Dynamics of Complex Systems (Studies in Nonlinearity). Westview Press Inc, 2003.

A. G. Wilson. Entropy in Urban and Regional Modelling. Pion Press, London, 1970.

M. Batty and P. A. Longley. Fractal Cities: A Geometry of Form and Function. Academic Press, San Diego, CA, 1994.

Michael Batty. Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals. The MIT Press, 2007.

H. A. Makse, S. Havlin, and H. E. Stanley. Modelling urban growth patterns. Nature, 377:608–612, 1995.

N. Salingaros. Principles of Urban Structure. Technie Press, Amsterdam, Holland, 2005.

Stephen Marshall. Streets and Patterns. Routledge, 2004.

Luis M Bettencourt, José Lobo, Dirk Helbing, Christian Kühnert, and Geoffrey B West. Growth, innovation, scaling, and the pace of life in cities. Proc. Natl. Acad. Sci. USA, 104(17):7301–6, 2007.

Alessio Cardillo, Salvatore Scellato, Vito Latora, and Sergio Porta. Structural properties of planar graphs of urban street patterns. Phys. Rev. E, 73(6):066107, 2006.

Paolo Crucitti, Vito Latora, and Sergio Porta. Centrality measures in spatial networks of urban streets. Phys. Rev. E, 73(3):036125, 2006.

S. Scellato, A. Cardillo, V. Latora, and S. Porta. The backbone of a city. Eur. Phys. J. B, 50(1-2):221–225, 2006.

Luis Bettencourt and Geoffrey West. A unified theory of urban living. Nature, 467(7318):912–3, 2010.

S. Porta, V. Latora, F. Wang, S. Rueda, E. Strano, S. Scellato, A. Cardillo, E. Belli, F. Cardenas, B. Cremenzana, and L. Latora. Street Centrality and the Location of Economic Activities in Barcelona. Urban Studies, 49(7):1471–1488, 2011.

Emanuele Strano, Vincenzo Nicosia, Vito Latora, Sergio Porta, and Marc Barthélémy. Elementary processes governing the evolution of road networks. Sci. Rep., 2:296, 2012.

EP Dakiell and ST McManus. Resilience, vulnerability, and adaptive capacity: implications for system performance. International Forum for Engineering Decision Making, 2004.

Daniel F. Lorenz. The diversity of resilience: contributions from a social science perspective. Natural Hazards, 2010.

TD O’Rourke. Critical infrastructure, interdependencies, and resilience. The Bridge, 37(1):22, 2007.

Dorothy A Reed, Kailash C Kapur, and Richard D Christie. Methodology for Assessing the Resilience of Networked Infrastructure. IEEE Systems Journal, 3(2):174–180, 2009.

Michel Brunet, Stephanie E. Chang, Ronald T. Eguchi, George C. Lee, Thomas D. O’Rourke, Andrei M. Reinhorn, Masanobu Shinozuka, Kathleen Tierney, William a. Wallace, and Detlof von Winterfeldt. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra, 19(4):733–752, 2003.

Stuart L. Pimm. The complexity and stability of ecosystems. Nature, 307(5949):321–326, 1984.

S Opricovic and G H Tzeng. Multicriteria Planning of Post-Earthquake Sustainable Reconstruction. Computer-Aided Civil and Infrastructure Engineering, 17(3):211–220, 2002.

C S Holling. Resilience and stability of ecological systems. Anna Rev Ecol Syst, 4:1–23, 1973.

C S Holling. The resilience of terrestrial ecosystems: local surprise and global change. In W C Clark and R E Munn, editors, Sustainable development of the biosphere, pages 292–317. Cambridge University Press, 1986.

CS Holling. Understanding the complexity of economic, ecological, and social systems. Ecosystems, 4:390–405, 2001.

C S Holling and L H Gunderson. Resilience and adaptive cycles. In L Gunderson and C S Holling, editors, Panarchy. Understanding transformations in human and natural systems., chapter 2, pages 25–62. Island Press, Washington, D.C., 2002.

Carl Folke. Resilience: The emergence of a perspective for social-ecological systems analyses. Global Environmental Change, 16(3):253–267, 2006.

Tatjana Kovalenko and Didier Sornette. Dynamical Diagnosis and Solutions for Resilient Natural and Social Systems. Planet@Risk, 1(1):1–41, 2013.

C S Holling. Engineering resilience versus ecological resilience. In Peter C. Schuize, editor, Engineering within ecological constraints, pages 31–44. National Academy Press, Washington, D.C., 1996.

Min Ouyang, Leonardo Dueñas Osorio, and Xing Min. A three-stage resilience analysis framework for urban infrastructure systems. Structural Safety, 36-37:23–31, 2012.

Paul J. Maliszewski and Charles Perrings. Factors in the resilience of electrical power distribution infrastructures. Applied Geography, 32(2):668–679, 2012.

N. O. Attoh-Okine, A. T. Cooper, and S. A. Mensah. Formulation of resilience index of urban infrastructure using belief functions. IEEE Systems Journal, 3(2):147–153, 2009.

Yi Li and Barbara J. Lence. Estimating resilience for water resources systems. Water Resources Research, 43(7), July 2007.

M. Omer, R Nilchiani, and A Mostashari. Measuring the resilience of the trans-oceanic telecommunication cable system. IEEE Systems Journal, 3(3):295–303, 2009.

P E Pinto, P Franchin, and A Lupoi. State of the art on methods for seismic risk assessment of road networks, volume 79. LESSLOSS Report, Deliverable, 2006.

Jie Li and Jun He. A recursive decomposition algorithm for network seismic reliability evaluation. Earthquake Engineering & Structural Dynamics, 31(8):1525–1539, 2002.

Leonardo Dueñas Osorio and Javier Rojo. Reliability Assessment of Lifeline Systems with Radial Topology. Computer-Aided Civil and Infrastructure Engineering, 26(2):111–128, 2011.

Francesco Cavallieri, Paolo Franchin, Pierre Gehl, and Bijan Khazai. Quantitative assessment of social losses based on physical damage and interaction with infrastructural systems. Earthquake Engineering & Structural Dynamics, 41(11):1569–1589, 2012.

P Franchin and F Cavallieri. Seismic vulnerability of a
complex interconnected infrastructure. In S Tesfamariam and K Goda, editors, Handbook of seismic risk analysis and management of civil infrastructure systems. Woodhead Publishing Limited, Cambridge, 2013a.

Pavlos Tanvakis and Yiannis Xenidis. Comparative Evaluation of Resilience Quantification Methods for Infrastructure Systems. Procedia - Social and Behavioral Sciences, 74(null):261–270, March 2013.

S H Strogatz. Exploring complex networks. Nature, 410(6825):268–76, 2001.

M. E. J. Newman. The Structure and Function of Complex Networks. SIAM Review, 45(2):167, 2003.

S Boccaletti, V Latora, Y Moreno, M Chavez, and D Hwang. Complex networks: Structure and dynamics. Phys. Rep., 424(4-5):175–308, 2006.

Marc Barthélemy. Spatial networks. Phys. Rep., 499(1-3):1–101, 2011.

R Albert, H Jeong, and AL Barabasi. Error and attack tolerance of complex networks. Nature, 406(6794):378–82, 2000.

Duncan S. Callaway, M. E. J. Newman, Steven H. Strogatz, and Duncan J. Watts. Network robustness and fragility: Percolation on random graphs. Phys. Rev. Lett., 85(25):5468–5471, 2000.

Reuven Cohen, Keren Erez, Daniel Ben-Avraham, and Shlomo Havlin. Resilience of the Internet to Random Breakdowns. Phys. Rev. Lett., 85(21):4626–4628, 2000.

G. Paul, T. Tanizawa, S. Havlin, and H. Eugene Stanley. Optimization of robustness of complex networks. The European Physical Journal B, 38(2):187–191, 2004.

B. Berche, C. von Ferber, T. Holovatch, and Yu. Holovatch. Resilience of public transport networks against attacks. Eur. Phys. J. B, 71(1):125–137, 2009.

Sergey V Buldyrev, Roni Parshani, Gerald Paul, H Eugene Stanley, and Shlomo Havlin. Catastrophic cascade of failures in interdependent networks. Nature, 464(7291):1025–8, 2010.

Gesara Satumtira and Leonardo Dueñas Osorio. Synthesis of modeling and simulation methods on critical infrastructure interdependencies research. In Kasthurirangan Gopalakrishnan and Peeta Srinivas, editors, Sustainable and Resilient Critical Infrastructure Systems, chapter 1, pages 1–51. Springer-Verlag, Berlin Heidelberg, 2010.

Alessandro Vespignani. Complex networks: The fragility of interdependence. Nature, 464(7291):984–5, April 2010.

Jianxi Gao, Sergey V. Buldyrev, Shlomo Havlin, and H. Eugene Stanley. Robustness of a Network of Networks. Phys. Rev. Lett., 107(19):195701, 2011a.

Jianxi Gao, Sergey V. Buldyrev, H. Eugene Stanley, and Shlomo Havlin. Networks formed from interdependent networks. Nat. Phys., 8(1):40–48, 2011b.

Xuqing Huang, Irena Vodenska, Shlomo Havlin, and H Eugene Stanley. Cascading failures in bi-partite graphs: model for systemic risk propagation. Sci. Rep., 3:1219, 2013.

Michael Southworth and Eran Ben-Joseph. Streets and the Shaping of Towns and Cities. Island Press, 2003.

R. Kinney, P. Crucitti, R. Albert, and V. Latora. Modeling cascading failures in the North American power grid. The European Physical Journal B, 46(1):101–107, 2005.

Forrest R. Pitts. A graph theoretic approach to historical geography. The Professional Geographer, 17(5):15–20, 1965.

Vito Latora and Massimo Marchiori. Efficient Behavior of Small-World Networks. Phys. Rev. Lett., 87(19):198701, 2001.

I. Vragović, E. Louis, and A. Díaz-Guilera. Efficiency of informational transfer in regular and complex networks. Phys. Rev. E, 71(3), 2005.

Paolo Franchin and Francesco Cavallieri. A framework for physical simulation of critical infrastructures, accounting for interdependencies and uncertainty. In 11th International Conference on Structural Safety & Reliability ICOSAR, New York, NY, USA, 2013b. Taylor & Francis.

E Cosenza and G Manfredi. L’Aquila: il progetto C.A.S.E. Ed. IUSS Press, Eucentre, Milano, 2010.

N. Ahmad, H. Crowley, and R. Pinho. Analytical fragility functions for reinforced concrete and masonry buildings and building aggregates of Euro-Mediterranean regions. University of Pavia, Pavia, Italy, 2011.

Dietrich Stauffer and Ammon Aharony. Introduction To Percolation Theory. CRC Press, 1994.

S. Dorogovtsev, J. Mendes, and A. Samukhin, Giant strongly connected component of directed networks. Phys. Rev. E, 64(2):025101, 2001.

Reuven Cohen, Keren Erez, Daniel Ben-Avraham, and Shlomo Havlin. Breakdown of the Internet under International Attack. Phys. Rev. Lett., 86(16):3682–3685, 2001.

R. G. Morris and M. Barthelemy. Transport on coupled spatial networks. Phys. Rev. Lett., 109:128703, Sep 2012.

Charles D. Brummitt, Kyu-Min Lee, and K-I. Goh. Multiplexity-facilitated cascades in networks. Phys. Rev. E, 85:045102, Apr 2012.