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A METHODOLOGICAL APPROACH TO ASSESS SEISMIC RESILIENCE OF CITY ECOSYSTEMS THROUGH THE COMPLEX NETWORKS THEORY

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Abstract

Earthquakes have always been representing a sleeper risk affecting local and global communities, as they are low-probability-high-risk events. In addition, being contemporary urban societies threatened by increasing exposure along with growing urbanization, resilience represents a key issue for modern societies, as the capability to withstand and recover from disasters. Understanding resilience as an engineering issue in the sense of ecosystems, cities can be modelled as complex networks, made of coexisting and mutually interacting physical and social components.

The proposed methodology aims at quantifying seismic resilience of city ecosystems according to a multidisciplinary approach. Resilience is evaluated while also ensuring an adequate level of sustainability, according to a social and human-centric perspective. A multi-scale approach is then performed in order to measure urban efficiency and systemic structural damage through the assessment of specific engineering measures.

Hence, to effectively do this, cities are modelled as hybrid social-physical networks (HSPNs), merging the infrastructural and human urban components. The efficiency of different hybrid network typologies is estimated, as nodes are modelled as residential buildings (citizen-citizen efficiency) or schools (service-citizen efficiency).

A real case study for the inner city Naples, namely the Quartieri Spagnoli area, is developed to validate the robustness of the proposed metrics. Synthetic HSPNs are also modelled accounting for different geometric shapes, according to the most common topologies in Europe and USA. Moreover, for each city shape, simulations are ran accounting for increasing city size, to study changes in resilience with the HSPN scale. As a point in matter, it is fundamental to account for specific urban dynamics in time and space. According to diverse studies in the literature, urban dynamics grow proportionally with a city size, becoming denser with the increasing scale, until a certain boundary, out of which such dynamics become unpredictable.

Seismic scenarios are simulated assuming for the earthquake's intensity to be deterministic in terms of the attained peak ground acceleration (PGA). The building portfolio for each modelled city is assumed to be constituted by reinforced concrete (RC) frame buildings, non-seismically designed and the vulnerability is quantified, by averaging fragility curves selected from the literature.

Mathematical and engineering measures are performed before and after the seismic scenario and during the recovery phases with a time-discrete approach, enabling to quantify the level of urban functionality and happiness of city inhabitants and environmental sustainability, as the urban resilience.

Hence, structural damage is evaluated in a systemic manner over the entire urban territory soon after an earthquake occurs, as a measure of the city efficiency drop. Two diverse recovery strategies are modelled and simulated to study the efficiency recovery and progress with a step-by-step procedure.

The proposed framework is a high-potential means of seismic risk mitigation, which can help local communities and support disaster managers to know the pre-event urban capacity and to face the post-event reconstruction. This can be even more effective when arguing at the local level, where recovery actions and financial sources are more easily manageable.

Keywords: disaster resilience; urban ecosystems; complex networks systems; sustainability; quality of life

1. Introduction

The inexorable trend of contemporary urbanization processes represents an important landmark in human history. Cities are the cornerstone of social and technological development, hence infrastructures and community assets are increasing in number, causing urban areas to be exposed and vulnerable now more than ever.
This phenomena highlights the need for novel approaches to urban management. In this context, natural hazards represent a major issue to deal with, according to an engineering and also human-centric perspective. In this paper, the capability of urban environments to withstand and response to natural disasters is investigated, as a fundamental requisite to build sustainable and resilient cities.

Urban resilience is understood as the engineering one according to the ecosystems theory, that is as the capability of a system to withstand external stresses and recover from them, to reach an equilibrium state, which can be the same of the pre-event or even a new one [1]. Hence, each action is as much effective as higher is the contribution it can give at increasing resilience. Such feature is strictly related to the capability of the studied system to be sustainable too. Indeed, the more the system is efficient in using its own resources to recover from a shock, the more it can strive for future sustainable development. This is even more evident when dealing with natural disasters affecting urban areas, where a more efficient recovery is guaranteed from a higher sustainability of the reconstruction phase, within the life cycle of a city. A city is, in fact, as much resilient as it is more sustainable during the hazardous event occurrence, that is when it is hit by an external stress and makes an effort to reconfigure its equilibrium [1][2].

An engineering-based methodology for resilience quantification is proposed. It allows to model any urban context as a complex network and to assess resilience as the efficiency progressively regained in each stage of the recovery, after a catastrophe occurred.

Since 2004 to present, six of the ten costliest catastrophic event are earthquakes. With this, because of the high rate of occurrence and to the huge economic and human losses caused by seismic events in last decades, earthquake scenarios are simulated to endorse the methodology [5]. The study proposes an integrated framework, which simulates the seismic event and enables to assess expected damages and to quantify resilience, to characterise the trend of urban efficiency, and systemic damage and resilience against the city size and shape.

According to Batty [4], since contemporary cities are typically fractals, the most effective use to model and simulate their behaviour is to deconstruct the rules that have been used in the past and design idealized cities. On the other hand, most of these realizations rarely provide the quality of life of their inhabitants as they are too simple with respect to the real workings of the development process. Hence, keeping with this, synthetic city models are developed, accounting for typical features of actual urban contexts. Hence, diverse cities are modelled, according to the most widespread topologies worldwide, with rectangular, circular, hexagonal and star shape. Each of these shape is then increasingly scaled and seismic scenario is simulated for it, to study the trend of urban resilience against the geographical configuration and to recognise its scaling relation with the city size. Also a real case study is performed to validate the proposed metrics, for the inner city Naples (Italy), the Quartieri Spagnoli area.

The infrastructure and the social networks are separately modelled and then overlaid and included in the related geographical space, to finally obtain a hybrid social-physical network (HSPN) [2][3]. Georeferring is performed through a geographic information system (GIS), which enables to integrate specific information on the built environment (location, structural typology, number of storeys, etc.). Two different HSPN typologies are modelled. The residential HSPN, which considers only residential buildings, is modelled to assess urban connectivity between pair of citizens. Furthermore, the school HSPN is modelled, which considers residential and school buildings, to study the efficiency of the school urban service.

The vulnerability of infrastructures - buildings and streets - is accounted for through the integration of probability-based models. Two recovery strategies are simulated, hypothesizing each HSPN to reconfigure in the pre-event equilibrium condition, after the earthquake occurrence. Efficiency measures are performed before the event occurrence, soon after it and in each stage of the recovery. This enables us to assess the local and global loss of functionality, hence to evaluate also the systemic urban damage. Finally resilience is calculated for each studied city context.

Results are analysed and compared to recognise differences between real and synthetic HSPNs, and to identify the most efficient city shape and the trend of resilience against the city size.

2. Quantifying seismic resilience according to the complex networks theory

Urban resilience is understood as a fundamental component of sustainability, as the capability of a city ecosystem to be sustainable during the hazardous event occurrence phase [1]. Basically, a city has to show readiness and promptness in disaster response and it has to effectively bounce back to an equilibrium condition, after an hazardous event occurrence.

This study proposes a novel approach for the resilience quantification, that enable us to contextually evaluate urban life quality, according to a humanitarian approach, disaster resilience and city robustness to structural damages. Indeed, damages suffered by an urban context are evaluated as the decay of the city's state of service after the occurrence of a seismic event in an integral fashion. Urban systems are analysed by accounting for each single component, and their mutual interrelations. As a consequence, the city model is built through the gradual annexation of such components, according to modern multi-scale approaches, from the lowest to the highest degree of network complexity.

Urban networks are modelled in a GIS-based environment, being composed of two interacting layers, representing the physical components and the social components, that is, the human dimension. Consequences and effects of network disruption are assessed by means of the graph theory, accounting for spatial distribution and network functionality. To do this, efficiency measures are assessed, previously, during and in the aftermath of a seismic event. Metrics are contextually evaluated for each layer, by also accounting for their interrelations. Finally they are integrated in a unique resilience indicator.

2.1 Modelling cities as hybrid social-physical networks

Each studied city is modelled starting at a smaller scale. According to graph theory the network of street paths and the network of buildings are modelled, hence they are overlapped in the geographical frame by means of a GIS-based software.

The resulting HSPN is a planar graph, defined in the Euclidean space, and composed of a set of nodes N and a set of edges L, hence being indicated as $G\ (N \cup L)$. Whereas, $N = N_b \cup N_s$ and $L = L_b \cup L_s$. Particularly, N_b represents the set of the buildings nodes, N_s is the set of the street junctions, representing crossings in the city's street paths, L_b represents the set of links connecting each city's building to each street junction and L_s the set of street links, connecting couple of street junctions.

In this study, both in the real case study of the Quartieri Spagnoli area and in case synthetic HSPNs are developed, two different case analysis are considered: the citizen-citizen case analysis and the school-citizen case analysis. In the former, when assessing the urban efficiency in guaranteeing connectivity between pair of citizens, the set of building nodes, N_b, represents only residential buildings. Indeed, in the latter case, N_b, is discretized in two further subsets: the residential buildings nodes, $N_{b,r}$, and the school building nodes, $N_{b,s}$, to compute the city efficiency in feeding citizens with the school service. As a result, in this case, the set of the building nodes is defined as $N_b = N_{b,r} \cup N_{b,s}$.

In each HSPN, distances between couple of nodes (i, j) are computed by calculating the Euclidean distance between them, d_{ij}^{eucl}. Paralleling this, the weight of links, associated to city's paths, are computed by means of the shortest path metric, d_{ij}, being the minimal sum of routes between them, having the minimal length.

According to the graph theory, a path between a couple of nodes i and j is an alternating sequence of nodes and edges leading from i to j, where each node is crossed only once. Hence, the shortest path metric enables us to evaluate a proxy for city connectivity between pair of nodes, by summing up the edges embedded in each possible path.

Once the physical network is modelled, the city's social component is computed through accounting for the inhabitants living in each city's building and for users attending each school. This is done by considering the total floor area of each structural typology and assuming 1 citizen each 30 square meters, as suggested by the database of the Italian Institute of Statistics, ISTAT [6].

Finally the physical and the social network are merged in the final HSPN.

Figs. 1 and 2, following, show the HSPN model for the real case study of the Quartieri Spagnoli area (Naples, IT) and for the synthetic cities, with different geometries.

As already outlined, in both case analysis, the residential HSPN and the school HSPN are modelled.

(a) (b) (c)

Fig. 1 – City map (a), residential HSPN (b) and school HSPN (c) of the Quartieri Spagnoli area (Naples)

The Quartieri Spagnoli area is located in the inner city Naples. It is a 3.57km perimeter and 0.57km^2 wide area. The building portfolio is mainly constituted by masonry buildings, of which about 600 are residential buildings and 17 are schools (kindergartens, primary, secondary and high schools). The area have about 30000 inhabitants and 3000 school users, which are respectively computed to buildings according to their floor area.

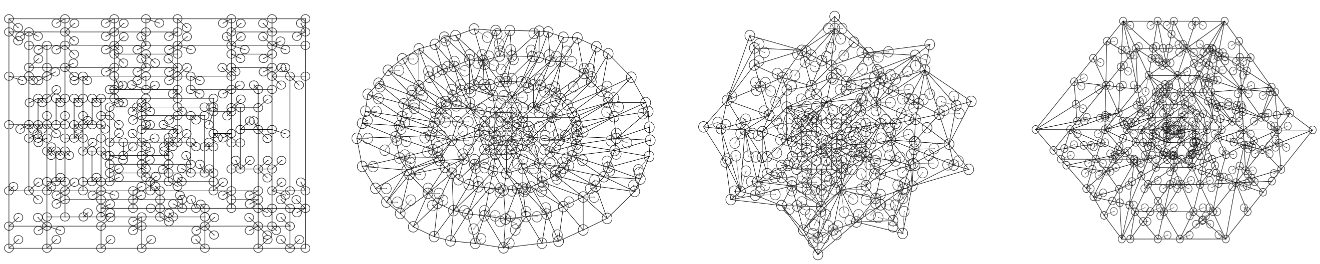


Fig. 2 – Synthetic HSPNs with rectangular, circular, star and hexagonal shapes

Buildings modelled in the sythetic HSPNs' case analysis are all regular RC frame buildings, typical 70s constructions. The number of storeys is assumed to be comprised between 2 and 5, with different incidence on the buildings portfolio: 10% 2-storey, 40% 3-storey, 30% 4-storey and 20% 5-storey. 1 citizen is assumed each 30sqm in this case too. Furthermore, according to the starting topology, a scale in size is performed, assuming for an increasing number of buildings to be embedded in the HSPN: 50, 200, 1250 and 5000 buildings. Fig. 3 shows the case of the rectangular city shape, as an example.

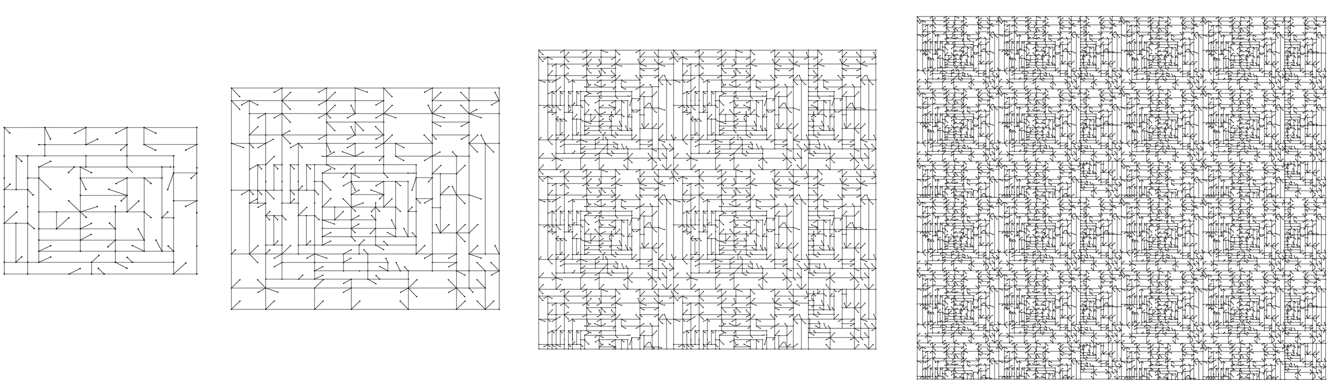


Fig. 3 – Scaling of the rectangular HSPN

2.2 Vulnerability assessment

Vulnerability of the built environment has been considered in both the case analysis by means of lognormal fragility curves from the literature. The study by Ahmad et al. [7] were selected, which assesses the seismic vulnerability of typically European RC and masonry buildings.

Statistics of the cited work are shown in Table 1:

Table 1 - Parameters of the seismic fragility curves by Ahmad et al. [7]

Structural Type	**μ**	**σ**
Masonry buildings	–1.03	0.35
RC buildings	–0.91	0.29

Because of the primary goal of the study is to investigate the HSPN disruption, only an extensive damage limit state is considered.

In case scenario analysis is performed for the Quartieri Spagnoli area, only parameters for masonry buildings are considered, due to its building portfolio consisting of masonry buildings. Analogously, in the synthetic HSPNs' case analysis only parameters for RC buildings are considered.

Besides, the severity of the simulated seismic events in the two case analysis are imposed in order to made them comparable. As it is notice, masonry buildings typically exhibit structural performances, which are worse than those of RC buildings. Hence, to make obtained values for the diverse HSPNs comparable, PGA values of impacting events are assumed such that they cause respectively 15% and 30% of buildings to collapse.

In case the building portfolio is all made of RC buildings (synthetic HSPNs), two diverse intensities of the seismic event are investigated. First of all an earthquake having PGA=0.30g is simulated, which causes 15% of buildings to collapse. Then, an earthquake having PGA=0.35g is simulated, causing damages to the 30% of buildings. Paralleling this, also in case a masonry buildings portfolio is analyzed (Quartier Spagnoli), two seismic events are simulated. The first one having PGA=0.25g (15% damaged buildings) and the second one having PGA=0.30g (30% damaged buildings).

As a case in point, also the fragility of the street network has to be computed. To do this, different widths are assigned to each HSPN's links, in both the case study. Thence, the ratio between each street's width and the height of adjacent buildings is calculated (Eq. 1), as the probability of street interruption. Finally, a stream of uniform numbers is generated in [0,1]. The comparison between the extracted numbers and the evaluated ratio for the each street link decides whether the street will be unusable or not, in the aftermath of the earthquake.

$$P_r(h,l)=\begin{cases}\dfrac{h}{l} & \text{if } 0<h<l\\ 1 & \text{if } h\geq l\end{cases} \tag{1}$$

where h is the height of the building and l is the width of the road.

Obviously, the higher is the ratio between the buildings' height and the road's width, the higher is the probability that the street link will be interrupted in the aftermath of the event.

2.3 Efficiency and systemic damage assessment

Typical connectedness metrics used for regular lattices or for random graphs may seem restrictive to gather the system's feature at a local and a global extent contextually, when dealing with a complex system. Hence, according to Latora and Marchiori [7] a specific metric can be used to assess the performances of a complex network, namely the global efficiency, E.

Particularly, if one considers people, information and goods flow concurrently along the network's edges, it can be assumed that the network's efficiency is inversely proportional to its shortest paths, d_{ij}. Furthermore, the shortest path length can be divided by the Euclidean distance between pair of nodes, d_{ij}^{eucl}, to normalize efficiency in [0,1]. The global network's efficiency can be then calculated by averaging such value on each couple of network's nodes, i and j, and having considered all possible paths between them, as shown in Eq. (2):

$$E = \frac{1}{H_{tot} \cdot (H_{tot} - 1)} \cdot \sum_{i \in B} H_i \cdot \left((h_i - 1) + \sum_{j \in (B \setminus I)} H_j \cdot \frac{d_{ij}^{eucl}}{d_{ij}} \right) \tag{2}$$

In case of urban HSPNs, this is particularized, being H_{tot} the total number of city's inhabitants, H_i and H_j are citizens using building nodes i and j, B is the set of the considered building nodes. d_{ij} is the shortest path's length, d_{ij}^{eucl} is the Euclidean distance, h_i is the number of citizens using buildings, which belong to the set I, that have zero distance from building i.

With this, the global efficiency is evaluated by accounting for citizens using each building node and for the mutual distances between such nodes and the street's nodes. Hence, it can be understood as the city's capability to connect inhabitants by considering residential buildings and the paths connecting them. In this case, the assessed urban service is the street network enabling citizens to move around the city.

In this paper, city's efficiency is evaluated also with reference to another urban service, as is the school service. In this case, the connectedness of the network is evaluated between residential and school buildings, through the street network edges and nodes. Basically, to do this, Eq. (2) is changed as shown following (Eq. (3)):

$$E_{cs} = \frac{1}{S_{tot} \cdot H_{tot}} \cdot \sum_{i \in S} S_i \cdot \left(h_i + \sum_{j \in (B \setminus I)} H_j \cdot \frac{d_{ij}^{eucl}}{d_{ij}} \right) \tag{3}$$

where a summation over the set S of the buildings representing facilities (in this case the set of schools) is performed. Here S_{tot} represents the summation of the total number of users using the facilities that supply the considered urban service, and that weights their importance in the HSPN. Instead, S_i is the number of citizens, i.e. the stakeholders, that benefit from the service supplied by the facility building $i \in S$.

In this view, the global efficiency of the HSPN can be evaluated before the event occurrence and soon after it, to measure the city's state of damage in a systemic fashion. Moreover, once a recovery strategy is designed to bounce back from the seismic event, it is also possible to assess efficiency at each stage of the recovery process to monitor the city's behaviour.

Substantially, the capability of a city to recover from a disaster is related to a huge quantity of variables. Usually decision makers choose the most feasible recovery strategy to undertake, depending on the time, money and human resources' availability. Issues related to this process affect the city recovery in different ways, being almost all related to time, t, so that they cannot be considered in detail. As a point in matter, the proposed approach totally removes the dependence of resilience on time, in order to avoid embedding further uncertainties in the evaluation process. To do this, HSPN efficiency is defined as dependent on the number of inhabitants being relocated in each recovery stage, C.

Hence, once efficiency is evaluated before, E_{pre}, and soon after the event occurrence, $E(C=0)=E(0)$, or in any recovery stage, $E(C>0)$, it is possible to define a function, called the recovery function, $Y(C)$, that returns the residual city system's capacity to feed citizens. Eq. (5) shows the formula:

$$Y(C) = \frac{E(C)}{E_{pre}} \tag{5}$$

where the ratio between the HSPN's efficiency before the event occurs (E_{pre}), when no citizen need to be relocated, and HSPN's efficiency after the event, when *C* citizens have been relocated, is evaluated, giving a measure of the residual efficiency of the HSPN.

Furthermore, also the dependence on the total state of damage is removed, enabling us to evaluated a normalized recovery function (Eq. (6)):

$$y(C) = \frac{Y(C) - Y(0)}{1 - Y(0)} \tag{6}$$

where *Y(0)* indicates the residual HSPN's efficiency soon after the event occurrence (relocated citizens *C=0*) and *Y(C)* indicates the residual HSPN's efficiency in each generic recovery stage (*C* citizens relocated).

The drop in efficiency between the pre-event and the aftermath of the earthquake can be then evaluated and normalized to the pre-event one, as a measure of the structural damage suffered by the HSPN, due to event (Eq. (7)).

$$D(C) = \frac{E_{pre} - E(C)}{E_{pre}} \tag{7}$$

and is defined in the close interval [0,1]. The observation of this indicator, becomes critical when observing the city's HSPN soon after the event occurrence (at the zero stage), *D(0)*.

Obviously the most the value of *D* tends to unity, the most the observed systemic damage is severe. As a consequence, the two limit cases can be defined as, *D(0)=1* "total damage", and *D(0)=0* "no damage".

2.4 Resilience quantification

Once efficiency is evaluated in each stage of the recovery and prior and after the earthquake occurrence, a recovery curve can be developed in the *C-E* plane (Fig. 4).

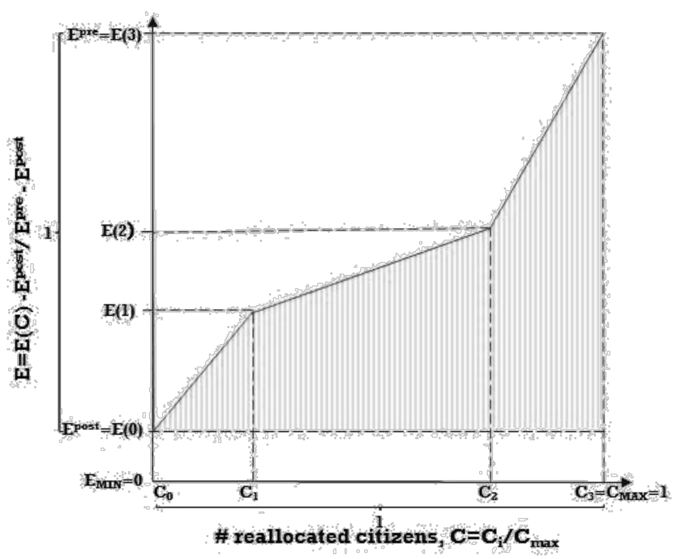


Fig. 4 – Typical trend of the recovery curve

The recovery curve represents the trend of the HSPN's efficiency against the number of citizens, that are gradually relocated in each recovery stage.

Resilience, as the HSPN capacity to respond to an event in this sense, is therefore the area under the recovery curve, and can be computed by convoluting efficiency through the recovery phases, according to Eq. (8):

$$R^E = \frac{\int_0^{C_{\max}} y(C)dC}{C_{\max}} \cong \sum_i \frac{[y_i(C_i) + y_{i+1}(C_{i+1})]}{2} \cdot \Delta C_{i,i+1} \tag{8}$$

where $\Delta C_{i,i+1} = \frac{C_{i+1} - C_i}{C_{\max}}$, that is the reallocated citizen share normalized to C_{max}. As a consequence resilience is defined in the [0,1] interval.

Nonetheless, according to the kind of issues one has to deal with, it could be necessary to evaluate resilience without removing its dependence on the total state of damage after the event has occurred, instead specifically accounting for it. This is the case, that a damage-dependent resilience metric is needed.

The proposed approach is basically the same as the previous one shown for the quantification of the damage-independent resilience. The only difference lays in that resilience is evaluated as dependent on the systemic damage, that is the global damage to the city's HSPN functionalities, *D*, as evaluated in Eq. (7).

Hence, resilience is evaluated by accounting for global city's efficiency, which is this time not normalized with respect to the pre-event performance level (Eq. (9)).

$$R^D = \frac{\int_0^{C_{\max}} D(C)dC}{C_{\max}} \cong \sum_i \frac{[D_i(C_i) + D_{i+1}(C_{i+1})]}{2} \cdot \Delta C_{i,i+1} \tag{9}$$

Paralleling this, by representing the recovery curve in the *C*-*D* plane (Fig. 5), being *C* the number of reallocated citizens and *D* the systemic damage level in each recovery stage, resilience is clearly represented by the area under the curve, also this time.

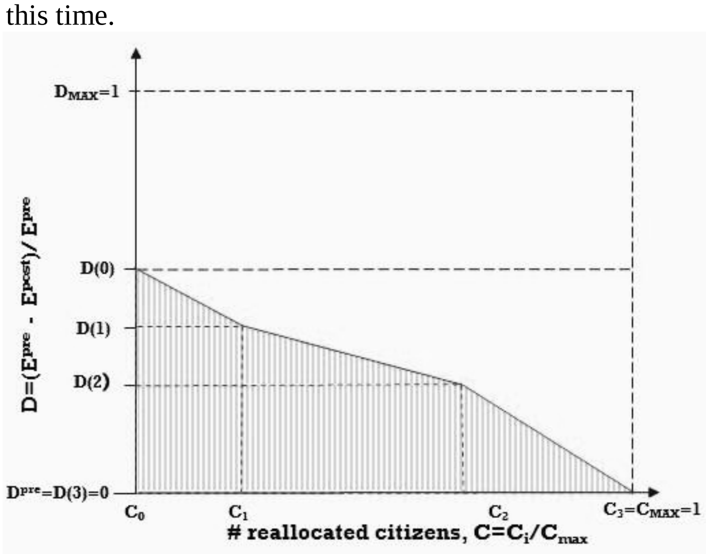


Fig. 5 – Recovery curve in terms of the systemic damage

This is because using a synthetic indicator to quantify resilience, may be misleading if one does not consider efforts done to bounce back to an equilibrium condition after an event. With this, one has to consider the damage condition, which the city starts from, with respect to its initial performance level, E_{pre}.

3. Comparisons and results from case studies

To validate the proposed approach and to verify the robustness of the proposed metrics, a real case study is developed. The historical centre of Naples, i.e. the Quartieri Spagnoli area, is modelled as a HSPN and earthquake scenarios are simulated to assess its resilience.

This area represents the core of the historical and cultural local tradition. It is mostly constituted by masonry buildings, accommodating small artisan shops, place of worships and typical local residences. Two different case analysis are run to evaluate the citizen-citizen and the school-citizen connectedness. Damage-independent and damage-dependent resilience are evaluated. Tables 2 and 3, following, show the results, also in terms of systemic damage and efficiency at the zero stage. Examples in terms of the HSPN configuration are also given in Fig. 6, in case of earthquake with PGA=0.25g where citizen-citizen efficiency is evaluated (Fig. 6-(a)) and in case of earthquake with PGA=0.30g where school-citizen efficiency is evaluated (red squared markers represent schools).

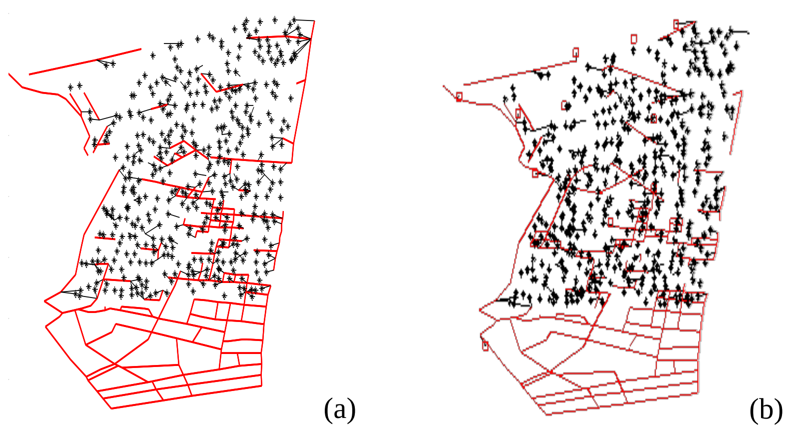


Fig. 6 – Post-event configuration of the Quartieri Spagnoli HSPN: (a) residential HSPN after an 0.25g earthquake, (b) school HSPN after an 0.30g earthquake

Table 2 – Results for the citizen-citizen case analysis

Citizen-Citizen analysis						
	E^{pre}	$E^{post\,*}$	Y(0) *	D(0) *	$R^{D\,*}$	$R^{E\,*}$
15%	0.62	0.09	0.15	0.85	0.33	0.60
30%	0.62	0.01	0.02	0.98	0.46	0.53
*median values						

Table 3 – Results for the school-citizen case analysis

School-Citizen analysis						
	E^{pre}	$E^{post\,*}$	Y(0) *	D(0) *	$R^{D\,*}$	$R^{E\,*}$
15%	0.12	0.02	0.13	0.87	0.41	0.55
30%	0.12	0.004	0.03	0.97	0.52	0.47
*median values						

The magnitude of the pre-event efficiency is very different in the two case studies. This is because efficiency is evaluated as inversely proportional to the shortest path distances. Hence, in the citizen-school case, being the number of schools in a minor quantity with respect to the residential buildings, obviously shortest path distances reveal to be higher. As a consequence, the resulting efficiency results to be lower with respect to the citizen-citizen case study.

Similar results for the two case analysis are observed, in terms of $E^{post}=E(0)$, $D(0)$, and $Y(0)$. Both in the citizen-citizen and the citizen-school case analysis, the efficiency drop, with respect to the pre-event, is about 83% in case 15% of buildings are damaged, and about 97% in the 30% case. Hence assuming damages to buildings 15% to increase (from 15% to 30% collapsed buildings), this results in a difference in the efficiency drop, which is proportional to it (about 13%).

The same trend is also observed for the systemic damage. It has to be noted that efficiency and systemic damage are inversely correlated. Indeed, when considering the 30% case analysis, for instance, $D(0)$=0.98 means that the HSPN is almost totally destroyed, hence its residual efficiency is minimal (E^{post}=0.01).

It is clearly evident, instead, that the recovery function is complementary to the systemic damage, being in this case $Y(0)$=0.02, hence equal to (1-$D(0)$).

Finally the HSPN resilience is observed. Both the damage-dependent and the damage-independent resilience indicators are defined in [0,1], hence being comparable their order of magnitude. On the other hand, they have different meaning.

When observing the damage-dependent resilience it is R^D= 0.33 in the 15% case analysis and R^D= 0.46 in the 30% case analysis, highlighting a 39% increase. Damage-dependent resilience increase with the damage level because a major ability to recover is exhibited by the HSPN. In fact, it bounces back to the pre-event equilibrium in the same number of steps, but starting from a severer damage condition, hence needing to reallocate many more citizens and to restore many more buildings. This means, that the most damaged HSPN has been quicker and more efficient in resource use than the least one.

Conversely, when considering the damage-independent resilience values, a 12% decrease is observed from the 15% to the 30% case analysis. This is because of this metric being directly related to the attained efficiency values, and to the drop suffered from the pre- to the post-event condition and across all the recovery stages.

Analogously to the Quartieri Spagnoli case analysis, scenarios are run also on the synthetic HSPNs models. Results are shown in Table 4 for the citizen-citizen case analysis:

Table 4 - Analysis' results for each HSPN's shape and size in terms of the median values for the 15% and 30% damaged configuration

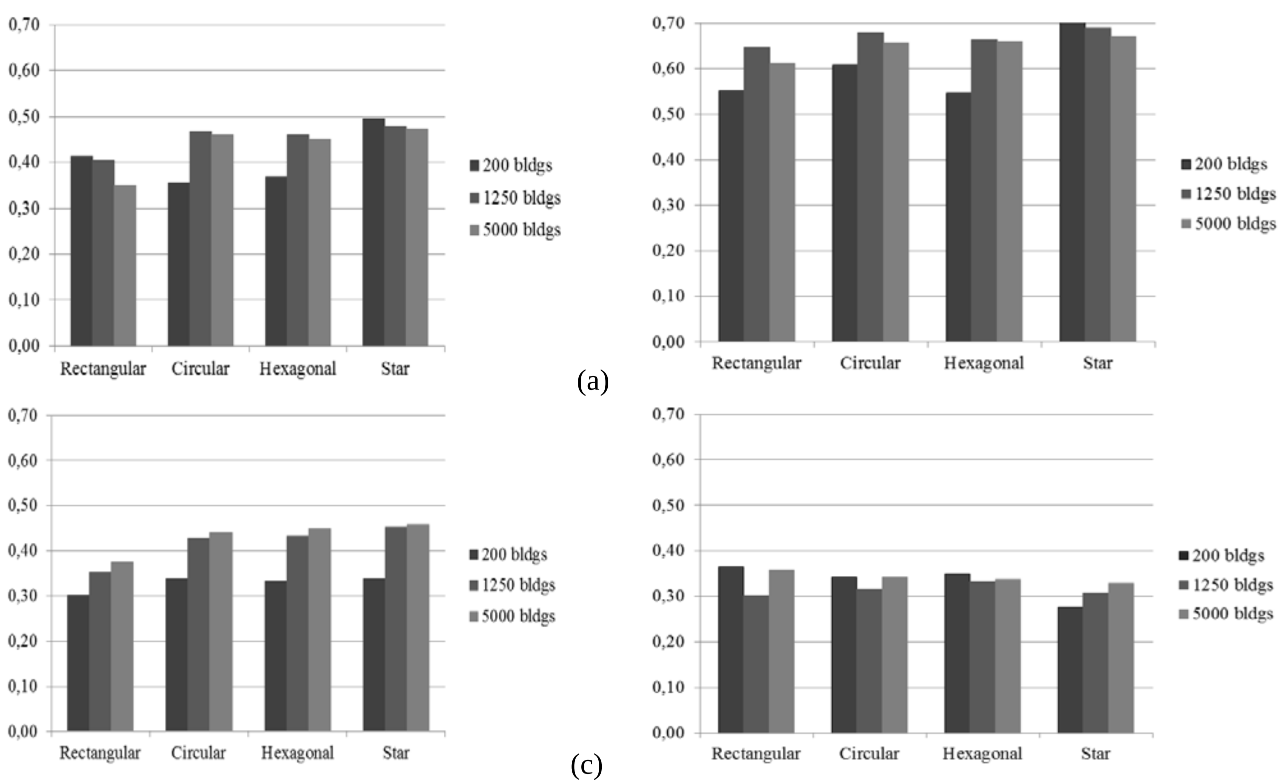
Citizen-Citizen analysis												
Shape	**15% collapsed buildings**						**30% collapsed buildings**					
	E_{pre}	E_{post}	Y(0)	D(0)	R^E	R^D	E_{pre}	E_{post}	Y(0)	D(0)	R^E	R^D
R50*	0.60	0.25	0.43	0.57	0.57	0.24	0.60	0.13	0.22	0.78	0.56	0.35
C50	0.94	0.51	0.54	0.46	0.55	0.22	0.94	0.20	0.21	0.79	0.53	0.38
H50	0.86	0.51	0.59	0.41	0.53	0.19	0.86	0.32	0.37	0.63	0.57	0.27
S50	0.91	0.54	0.60	0.40	0.57	0.17	0.91	0.32	0.35	0.65	0.57	0.28
R200	0.75	0.38	0.50	0.50	0.51	0.25	0.75	0.13	0.17	0.83	0.48	0.43
C200	0.93	0.43	0.46	0.54	0.51	0.27	0.93	0.16	0.17	0.83	0.48	0.43
H200	0.93	0.45	0.49	0.51	0.48	0.28	0.93	0.22	0.24	0.76	0.47	0.41
S200	0.90	0.37	0.41	0.59	0.50	0.29	0.90	0.07	0.07	0.93	0.46	0.49
R1250	0.75	0.39	0.52	0.48	0.53	0.22	0.75	0.07	0.10	0.91	0.52	0.41
C1250	0.95	0.23	0.24	0.76	0.46	0.40	0.95	0.01	0.01	0.99	0.41	0.58
H1250	0.93	0.20	0.22	0.78	0.54	0.36	0.93	0.01	0.01	0.99	0.48	0.51
S1250	0.93	0.20	0.21	0.79	0.50	0.39	0.93	0.01	0.01	0.99	0.43	0.57
R5000	0.78	0.40	0.51	0.49	0.53	0.23	0.78	0.08	0.10	0.90	0.55	0.41
C5000	0.94	0.18	0.19	0.81	0.55	0.37	0.94	0.00	0.00	1.00	0.49	0.51
H5000	0.92	0.20	0.21	0.79	0.53	0.37	0.92	0.00	0.01	0.99	0.49	0.52
S5000	0.92	0.14	0.15	0.85	0.56	0.36	0.92	0.00	0.00	1.00	0.48	0.52

* acronyms of HSPN models have to be understood as: R= rectangular, C= circular, H=hexagonal, S= star. The numbers following the first term indicate the number of modelled buildings, for instance R200 indicates the rectangular shape with 200 buildings.

Similar results can be observed in terms of the order of magnitude between the real case study and that of synthetic HSPNs. Low variations across HSPNs' shapes and sizes are observed, in terms of the damage-independent resilience metric. On the other hand, damage-dependent resilience shows higher discrepancies, also exhibiting an increasing trend with the HSPNs size. This is due to the higher damage level suffered by bigger HSPNs, which results in a higher number of citizens to be relocated, and a higher number of streets and buildings to be restored. Moreover, the lower variability of the damage-independent resilience metric is due to its normalization, which is done with respect to the slope between the pre- and the post-event efficiency. Hence, in this case, the initial efficiency of the HSPN is not accounted for.

The damage-dependent resilience metric, instead, is assessed by integrating the systemic damage parameter, which is normalized only with respect to the pre-event efficiency level. With this, the HSPNs' capability to "bounce back" to the pre-event equilibrium, is assessed while contextually considering the impact of the seismic event, that is represented by the magnitude of the post-event efficiency.

Similar results can be observed in the school-citizen case analysis, with reference to which the trend of damage-independent and damage-dependent resilience is highlighted in Fig. 7, following, to show the trend of resilience with the HSPN size and shape:



(a) (b) (c) (c)

Fig. 7 – Hystograms of the damage-dependent resilient in case 15% (a) and 30% (b) buildings are damaged, and damage-independent resilience, in 15% (c) and 30% (d) damage case

Results in terms of the HSPNs' resilience, R^D and R^E are not always in agreement in this case too, due to their diverse correlation to the damage suffered by the HSPN.

In terms of the HSPN shape, in both the case analysis and both the seismic scenarios, the rectangular HSPN reveals to be the one suffering less damages almost in all the cases, being followed by the hexagonal HSPN. Hence a major robustness of such HSPN's shapes can be asserted. In fact, in terms, of the systemic damage both rectangular and hexagonal shapes exhibit the lowest values. Paralleling this, they result to be the most resilient geometries in terms of the damage-independent resilience, R^E.

On the other, when considering the damage extent, the star-shaped HSPNs result to be the most resilient, according to the damage-dependent resilience metric, R^D. This can be understood as the star HSPN bounces back to the pre-event efficiency within the same number of stages of the other HSPNs, starting from a severer level of damage.

The assessed resilience is also observed with reference to the HSPN size. According to Bettencourt et al. and Lobo et al. [12][11], processes being governed by community-based dynamics usually exhibit a sublinear trend against the city size, while processes being governed by economies of scale exhibit a superlinear trend. Nonetheless, when observing the trend of the proposed resilience metrics against the city size, a scaling can be observed in the citizen-citizen case analysis for the damage-dependent resilience metric, while the same cannot be asserted in the school-citizen case, since fluctuations are observed in resilience values, in both the case analysis, when compared with the HSPN scaling.

Finally, it can be asserted that the two proposed resilience metrics are not mutually exclusive, but they can be used complementarily, since they catch diverse aspects of the urban resilience.

R^D is useful to compare urban contexts being stroke by the same catastrophic event, to contextually evaluate the systemic damage and the bouncing back capability at the local level. Paralleling this, R^E can be used to compare urban contexts, which are very different or that have been struck by different event typology. Hence, the methodology has got the potential to be used to compare best practises, according to the event typology, even though they occurred in different geographical and urban contexts, enabling for observations and understandings related to resilience issues on the global scale.

4. Conclusions

Cities can be understood as complex systems where physical and social components coexist and are strictly interrelated. Building sustainable cities, while enhancing their resilience against catastrophic natural and human-induced events, is therefore a major issue.

The present paper focus on natural events, particularly earthquakes. An earthquake is an unpredictable event, which strikes urban physical components and the services they supply to citizens. As a consequence, severe injuries to the human component and their life quality are observed too. The methodology adopted in this paper aims to quantify the resilience of urban centres, specifically their coping capacity and robustness against earthquakes after different levels of damage. Two diverse resilience metrics are proposed and evaluated, the former being independent on the initial state of damage after the seismic event occurrence, and the latter being dependent on it.

First the city is modelled as a hybrid social-physical network (HSPN), embedding physical and social components. Then scenario analysis are performed for the real case study of the Quartieri Spagnoli area (Naples) and sixteen artificially modelled HSPNs with diverse shape and sizes. The urban connectedness level between couple of citizens (residential HSPN) and between the school service and the city inhabitants (school HSPN) are also investigated for all HSPNs modelled.

Furthermore, comparisons are performed between HSPNs' shapes and sizes, with regards to damage-dependent and damage-independent resilience. The proposed framework has the potential to be applied to a multiplicity of case studies, focusing on several diverse urban features and urban risks. Experimental results show a clear decline of the HSPNs' efficiency in the aftermath of the seismic event, which is gradually recovered. Obviously the more intense is the earthquake, the more buildings and streets are damaged, and the more citizens are reallocated too.

The robustness of the proposed framework is underlined. In fact, the model results to be consistent with the real case study city (the Quartieri Spagnoli HSPN), therefore proving its strength as one way to project possible damage to and resilience of urban form. As a result, comparable results are observed for the real HSPN and artificial HSPNs with a similar number of citizens and buildings.

Moreover, urban form reveals in having a significant impact on urban efficiency in terms of service delivery and on urban resilience after a natural disaster. In particular, a 'star' HSPN shape and a rectangular HSPN shape exhibit the greatest resilience. Although, this is partially because they do not have to return to such efficient equilibria, and partially because they do not experience the same level of systemic damage as more typical circular or hexagonal HSPN shapes.

Based on the observed systemic damage and efficiency in the pre- and post-event, the two resilience metrics (damage-independent and –dependent) seem to be collaterals. The former enables us to compare the resilience of different urban environments to diverse events. The latter enables us to assess a city's capability to recover from varying levels of damage. As a consequence, contextual observation of such metrics is recommended.

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