Modeling the interdependency between buildings and the electrical distribution system for seismic resilience assessment

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Modeling the Interdependency Between Buildings and the Electrical Distribution System for Seismic Resilience Assessment

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ABSTRACT: The complexity of large-scale power networks, together with their increasing ageing and obsolete design, implies an intrinsic fragility with respect to natural disasters, such as strong earthquakes. The investigation of the interdependencies among different critical infrastructures is fundamental to prevent possible cascading effects and frequent unserviceability. This paper aims at studying the effects of a seismic event on a large-scale virtual city, implicitly modeling the interdependency between the buildings and the electric distribution network. A consistent methodology to assess the resilience of the urban electric power distribution system is herein introduced and validated. Furthermore, a new resilience index is also introduced and compared to others available in the literature. The index is able to properly describe the network resilience, by taking into account aspects such as redundancy and resourcefulness. The developed methodology allows to investigate the impact of extreme events on the electric power distribution system also in case of scarce input data.

Keywords: Power Network; Infrastructure Interdependency; Resilience; Earthquake Simulation; Virtual City.

1 INTRODUCTION

Most of modern infrastructures rely on power networks to provide essential services to the community. *Power transmission and distribution systems* have as main purpose to transfer electric energy from generating units to the customers at various locations [1]. The first part of a network, i.e. the *transmission* system, spans long distances at high voltages (usually in the range 60-750 kV). The second one is instead divided into a medium and low voltage *distribution* systems. The latter serves the domestic and small commercial customers and operates at low voltages (e.g. 230 V single-phase, 400 V three-phase in Europe). The *transmission* system is usually overhead, while the *distribution* system can be both overhead and underground, despite modern cities prefer to let the system run underground as it is safer and more efficient. The *transmission* system is a meshed grid, composed of stations as nodes and transmission lines as edges, while the *distribution* system is operated as tree-like network, that usually follows the main streets of a city. The approach proposed by FEMA [2] is mostly adopted in literature to assess the seismic performance of transmission and distribution systems [3; 4].

Many findings and innovations aiming at improving power networks' seismic resilience are the results of past failure scenarios and further investigations. Several events worldwide proved how fragile electric power systems can be to seismic action. For example, in 2011 the earthquake stroke Christchurch in New Zealand [5] and both the sub-transmission systems (part of the transmission system operated at lower voltage [6]) and the distribution systems failed. In that event, almost the 80% of the inhabitants remained with no electric power. The main infrastructure was restored in five days, but some areas remained unsupplied for more than a month. Therefore, interdependencies among the power network and other infrastructures is the crucial aspect for properly investigating cascading effects and damage amplification.

In literature several studies and methodologies have been developed to assess post-earthquake interdependencies between different infrastructures [7]. Taking again the 2011 New Zealand earthquake as an example, Kongar et al. [8] analyzed the similarities with the L'Aquila earthquake occurred in 2009 in Italy to provide a succinct and holistic overview on the functional impacts, resilience attributes and interdependency issues observed during the emergency management and recovery phases for infrastructures.

The 2010 Maule and 2011 Tohoku earthquakes were instead compared by Krishnamurthy et al. [9] to assess the extent to which particular failure modes and restoration processes are prevalent in two different cases. Results show that there is a strong coupling between the restoration of power and telecommunication infrastructure systems in both Japan and Chile events. Data from the Tohoku earthquake was also used as case study in the work of Lee et al. [4] who developed an agent-based inoperability input-output model with a focus on damage propagation from a component level to a system level. Research about such destructive events is crucial to underline various aspects that should be taken into account in the resilience assessment and to develop new technology to improve networks' resilience, such as microgrids [10], innovative seismic isolation systems [11], retrofit techniques [12], mitigation strategies [13], and Decision Support Systems (DSS) such as CIPCast [14].

Virtual case studies represent also an effective tool to test these methodologies as they allow to properly model infrastructure taking into account interdependencies [15-17].

A challenging task, given a certain network, is to identify critical components where failure may occur. As documented in [18-20], the weak point of electric power systems is at the substation level and transformers are expected to be the non-structural elements that fail most frequently. Failure depends on different constructive factors, which are related to the voltage level: the higher the transformers' voltage, the higher their vulnerability [19]. International codes and guidelines, such as the ESTI 248 [21] and the IEEE 693 [22], suggest different types of solutions to properly anchor non-structural elements to limit damages. Most of these solutions were proposed after notorious events, such as the 2014 South Napa and La Habra earthquakes, which led to significant improvements in power grids' performances, as reported by [18].

A comprehensive methodology for seismic resilience assessment was developed by [3] who considered a real distribution network in Chile. A four-step procedure was proposed to model the earthquake, the network component fragility, the network outages, and the impacts on network operation. Using a GIS (Global Information System) approach to the problem the grid resilience was evaluated in terms of *Energy Not Supplied* (*ENS*). This approach inspired also the development of the *Similarities Design Method* [23], where the fragility of the electrical components was employed to assess the resilience of the distribution system. However, this approach neglects the interdependency of the power distribution network with the buildings where the substations are usually located.

This paper focuses on damages due to ground motion on urban distribution systems. In this kind of systems, the nodes are substations enclosed in buildings. In their research, Cavalieri et al. [1] reported a complete overview of the main recent works on fragility functions of electric power system components, with the indication of the methodology used to evaluate the curves, the components considered and the damage states and indices. The fragility of main components towards earthquakes is generally expressed in terms of peak ground acceleration (PGA). Together with the fragility functions, the corresponding damage scales are presented. However, sub-systems located in enclosures might fail not only for their own fragility, but also for the damages that can possibly occur to the buildings hosting them and so the damages to electrical components should be appropriately modelled by defining the interdependence between the built environment and the electrical distribution infrastructure.

In the present research, substations' fragility is connected to the buildings' fragility (*Density Design Method*) implicitly modeling the interdependency between the buildings and the electric distribution network. Since real data describing power distribution systems are often not freely available, building and street information are used to design the infrastructure. The *Similarities Design Method* is herein considered integrated with the *Density Design Method*, as complemental components of the proposed methodology to face the problem of grid resilience. It is developed to be employed by city planners to optimize the design of their electric power systems.

The electric power system is represented by sub-transmission system nodes and distribution system nodes. This allows to model a more detailed power network of the urban area, and to extend the model also to the sub-transmission system facilities in case of large and rare events. The case study to apply the proposed methodology is a large-scale virtual city called Ideal City [17]. The resilience of the network is computed by using as input the collapsed buildings and the areas without electric power after a simulated seismic scenario. Results are presented in terms of *ENS* and another index defined by the Italian National Authority for Power, Gas, Water and Wastes [24]. Furthermore, a new index, called the *Power Resilience Index* (*PRI*), is introduced. The novelty of the *PRI* index is to consider the redundancy and resourcefulness as dimensionless coefficients, by allowing the comparison of the resilience performances related to different networks regardless their extension and number of customer. Furthermore, *PRI* is able to highlight the initial resilience of the network, which is strictly depending on the components installed.

2 PROPOSED METHODOLOGY

2.1 *Resilience Indices*

The Resilience of power distribution networks is part of the political and legislative discussion in several countries. For instance, the Italian Regulatory Authority for Power, Gas, Water and Wastes suggests to compute the resilience of a power grid focusing on the risk of leaving users without electric power in case of natural hazards or extreme weather conditions [24]. Different indices have been proposed such as *IRI* (Risk Index) which is calculated as shown in Eq. (1):

$$IRI = NUD \cdot PD \tag{1}$$

where *NUD* is the number of users with no electric power and *PD* is the probability of disservice, defined as $PD = 1/T_R$ where T_R is the return period of the event, calculated accordingly with the European standard CEI EN 50341 [25]. Another index, called *IRE* (Resilience Index), can be defined as (Eq. (2)):

$$IRE = T_R / NUD \tag{2}$$

that is also the inverse of the index defined in Eq. (1). Resilience indices can also be defined in terms of *ENS* as illustrated in Eq. (3):

$$ENS = NUD \cdot P_{N,U} \cdot t_U \tag{3}$$

where $P_{N,U}$ is the nominal power in kW of a single customer, t_U is the duration of the power interruption. This index highlights the progressive network restoration and gives an immediate representation of the earthquake overall effects.

These indices focus mainly on power network failures, but they do not take directly into account in their formulation all the resilience characteristics [7; 26], which are: (i) *rapidity*, the system capability to quickly react and achieve results to limit the human and economic losses; (ii) *robustness*, the ability of elements, systems or other units to withstand a certain level of stress without suffering degradation or loss of functionality [27]; (iii) *redundancy*, the possibility for a system to be fed through alternative paths, while the usual ones are under restoration; (iv) *resourcefulness*, the system managers capability to identify weaknesses and mobilize resources to reduce the effects of a likely damage.

To include these aspects, a new index called the *Power Resilience Index* (*PRI*) is herein introduced (Eq. (4)):

$$PRI = \int_{t_1}^{t_2} T_{rr} \cdot n_{usub} \cdot \gamma_{path} \cdot PG \cdot dt \tag{4}$$

where:

- T_{rr} is the *Transformer Restoration Rapidity* that can assume the following values: 1 when there are only transformers with rated power equal to 0.4 MVA; 0.67 for 0.4 and 0.63 MVA transformers; 0.57 when 0.4, 0.63 and 1 MVA transformers are used. These values are derived from FEMA data about transformers restoration. The concept of rapidity aims to differentiate the case of network with only 400 kVA transformers from the case of network with different types of transformers. The types of installed transformers have an impact on the restoration process. For example, the network with only 400 kVA installed transformers is characterized by quicker restoration phase and higher T_{rr} . Thus, the higher is the T_{rr}, the higher is the *PRI*, and the network results to be more resilient
- n_{usub} is the percentage of undamaged substations and represents the robustness of the network. It is expressed as the ratio between the number of undamaged substations after a disruptive event and the total number of substations in the network.

- γ_{path} is related to the presence of alternative lines that can supply a neighborhood from surrounding areas. This value ranges between 0 and 1, where 0 means a total lack of alternative paths and 1 describes the case of complete connection among the various neighborhoods. The value of γ_{path} has to be updated according to the collapse probability of the system alternative paths in case of earthquake. The range of variation of γ_{path} parameter refers to independent paths (composed of different set of branches) supplying that node. If the total number of independent paths supplying one node is two, and one of them is out of service, then the value of γ_{path} will be 0.5 (half of the paths are available). If it was three, and one of the paths was not available, the value of γ_{path} would be 2/3, and so on.
- *PG* depends on the availability of portable generators to be used in the first hours after a disaster. This value varies between 0, i.e. no available generators in the region, and 1, when all the recovery areas could be quickly supplied with temporary solutions. The value of *PG* can be tuned on the basis of the experience of the Distribution System Operator (DSO). For example, let us suppose that a portable generator is usually available in 30 minutes. So, if the DSO expects that the portable generators can be in place in maximum 30 minutes, *PG* will be 1. If instead the expected time for that particular condition is 1h, that *PG* will be 0.5.
- t_1 and t_2 define the analysis' range of time. The *PRI* is not a resilience evaluation at a specific time, but it includes the evolution of the described parameters over the selected time.

Eq. (4) is inspired by the definition of resilience given in [26] and adapted to the power distribution network. The novelty of the *PRI* index is to directly incorporate in its formulation dimensionless coefficients referring to redundancy (γ_{path}) and resourcefulness (*PG*) related to the power network.

2.2 *Proposed methodology*

The proposed methodology (**Figure 2-1**) is based on two main components: the *Similarities Design Method* [23] and the *Density Design Method*. The procedure starts with the collection of information about the built environment. The objective would be to create a database that contains all the details needed to obtain fragility functions for each building. This is usually a challenging and time-consuming task since frequently stakeholders and public authorities cannot share sensitive data. The methodology allows to follow two approaches depending on the available information. If the collected data are not enough to build the fragility functions, then the *Similarities Design Method* can be used. In this case, a typical grid is selected from a reliable database and applied in each neighborhood, adding or deleting some buses and checking the load flow according to the covered area. On the other hand, if the fragility of each structure can be calculated, a more detailed approach can be used (*Density Design Method*). In this case, the grid can be designed from population density data and the corresponding power demand. The fragility of network components is assumed to be the same of the buildings where they are installed. The two approaches are not alternative but complementary as the first one is focused on the electrical components, while the second one on the interdependency with the built environment. At this point, the resilience indices described in section 2.1 can be evaluated. Based on this estimation, the city planners can make decisions and eventually improve the resilience of the urban distribution system.

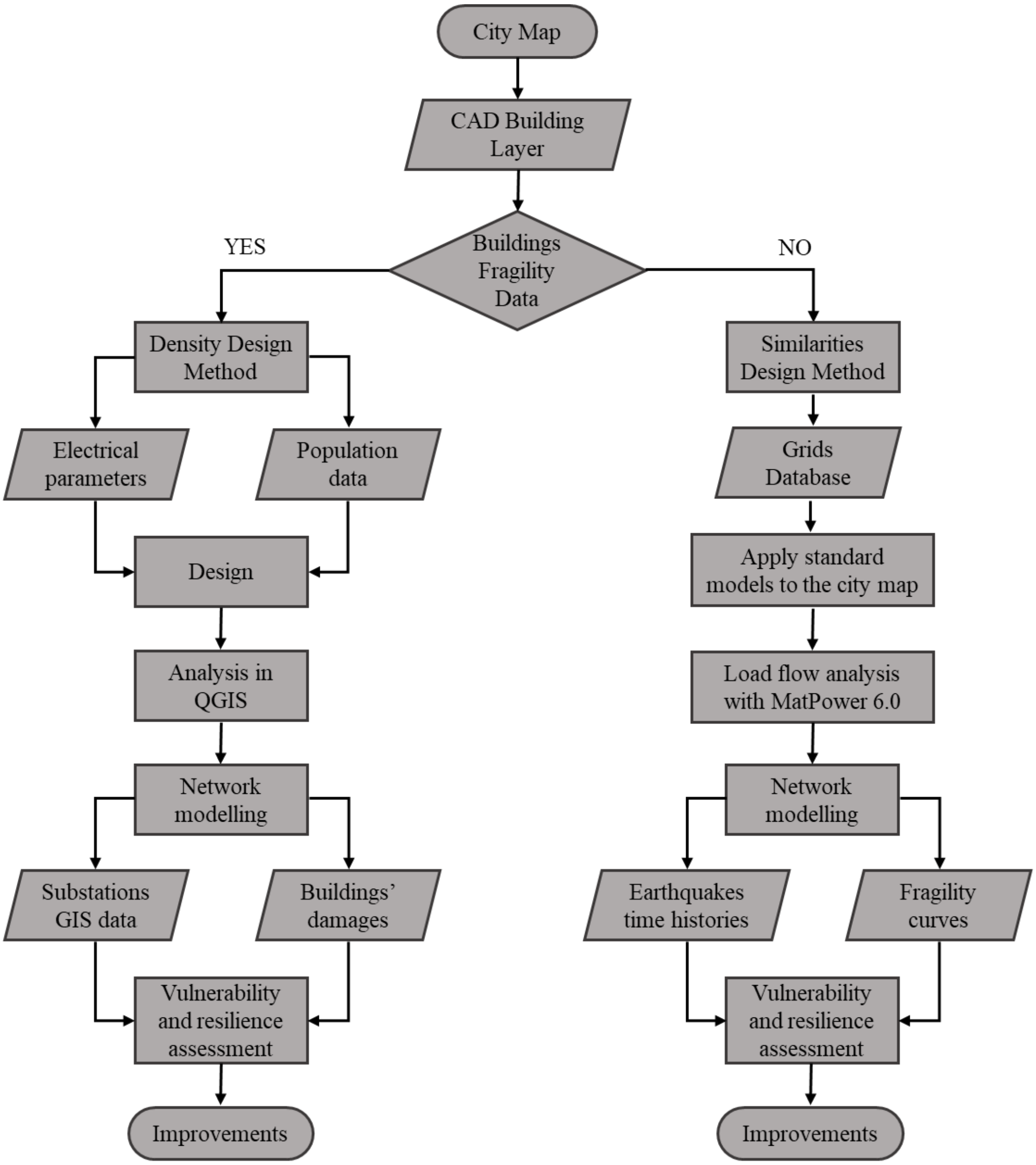

Figure 2-1. Flowchart of the proposed methodology.

2.2.1 *The Similarities Design Method*

The main idea of this method is to use existing testbeds to find an electric grid compatible with the case study that one wants to analyze. The Distribution System Operators Observatory of JRC (Joint Research Centre, Ispra, Italy) released a technical report about representative standard networks [28]. They collected data from 79 out of 190 European DSOs, that are representative of the 70% of the electric power supplied by all DSOs. This information was used to identify 36 indicators about network structure, network design, and distributed generation, which helped to build representative distribution networks using also the *Reference Network Model* (*RNM*) developed by Domingo et al. [29]. The "urban" network from JRC database is used for most densely populated districts, while the "semi-urban" is used for the surrounding areas. These networks provide information about HV (high voltage), MV (medium voltage) and LV (low voltage) buses with coordinates, branches, electric parameters and protections. However, LV data is relevant only for the definition of the total number of consumers and not to determine the actual buses' position. Thus, only HV and MV buses are explicitly considered in the model. The position of the HV/MV substations has been chosen to be as close as possible to the real network topology. Once the HV/MV substations have been inserted in the map, the topology of the JRC network has been adapted to take into account the built environment of the Ideal city and, if needed, the initial topology has been modified by adding new feeders or by deleting some nodes, but all the modifications have been checked by the network calculation.

A graphical description of the *Similarities Design Method* is illustrated in **Figure 2-2**.

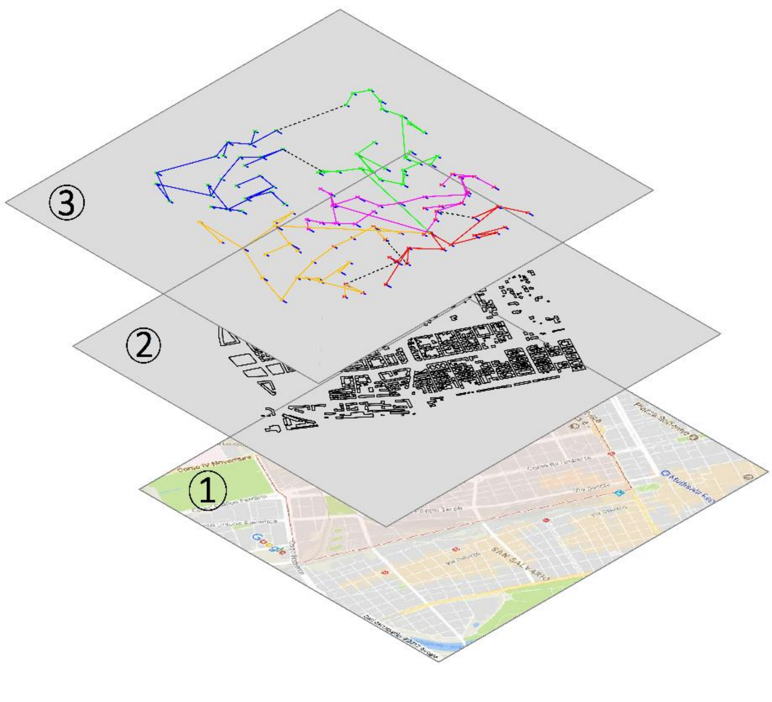

Figure 2-2. Graphical description of the *Similarities Design Method*.

Layer number 1 represents the map of the city that contains the geospatial information needed to define the location of the power grid components. It can be simply downloaded from web mapping services (e.g. Google Maps, OpenStreetMap, etc.). The second layer contains the buildings together with the related available information. This allows to better detail the distribution network as the load conditions vary block by block: areas with a larger number of buildings are associated with a higher demand of electric power and therefore with more distribution networks. Layer number 3 is the power infrastructure adapted from the JRC database to fit the actual case study. Once the network is modelled, the load flow analysis is performed through *Matpower 6.0*, a package of MATLAB [30] developed by PSERC (Power Systems Engineering Research Centre) at Cornell University [31]. *Matpower 6.0* uses the Newton Raphson (NR) algorithm to solve the nonlinear problem of computing the load flow on the entire damaged grid. This allows to obtain more precise and detailed results with respect to a simple connectivity analysis. An example of how to realize a simplified grid for a neighborhood of Ideal City through the *Similarities Design Method* is presented in [23].

2.2.2 *The Density Design Method*

The herein proposed *Density Design Method* allows for a more detailed analysis of the system. In this case the power grids are specifically designed, instead of taking advantage of an existing database. Mainly, three design aspects are considered: (i) population and its density, (ii) electric power load density, (iii) engineering constraints (e.g. feeders' length, load types, buses' redundancy, etc.). The urban area is then divided into neighborhoods to locate substations and apply medium voltage schemes. In this study all MV substations have a voltage of 22 kV and loads are defined according to the European technical report [28]. Table 1 reports the assumed distribution of load types according to the best practice.

Type of transformer [kVA]	**Percentage**
400	60%
630	30%
1000	10%

Table 1. Share of the different types of transformers.

3 CASE STUDY

This section shows the application of the proposed *Density Design Method* to a virtual large-scale city called Ideal City. This testbed is based on the city of Turin in Italy and the model includes many critical interdependent infrastructures. The *Density Design*

Method was used to design the power distribution network for each neighborhood in which the city is divided (**Figure 3-1**) [32]. The software used are AutoCAD [33] and QGIS [34] since they allow to draw the network as a georeferenced graph and store information about each component in a database. Real data from official reports [32] were used to build the model when available, while assumptions were made for missing information.

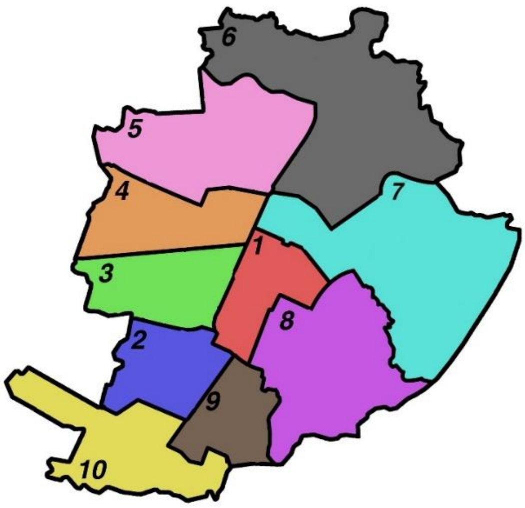

Figure 3-1. Map of Ideal City neighborhoods.

As an example, the application of the *Density Design Method* to neighborhood number 1 is hereafter provided. The design input parameters are listed in Table 2. The population data and the related power demand are also necessary to plan the grid. According to them, the substations are designed and located in the map. **Table 3** reports the resulting output characteristics that are graphically shown in **Figure 3-2**.

Parameters	**Values**
Area	6.879 km^2
Population Density	11,652 inhab./km^2
Population	80,152
Designed Load density	8 MVA/km^2
MVA estimated	55
Number of buses estimated	104

Table 2. Neighborhood number 1 Design Input Data.

Parameters	**Values**
0.400 MVA buses installed	65
0.630 MVA buses installed	33
1 MVA buses installed	10

Number of buses installed	108
Number of users supplied	81,034

Table 3. Neighborhood number 1 Design Output Data.

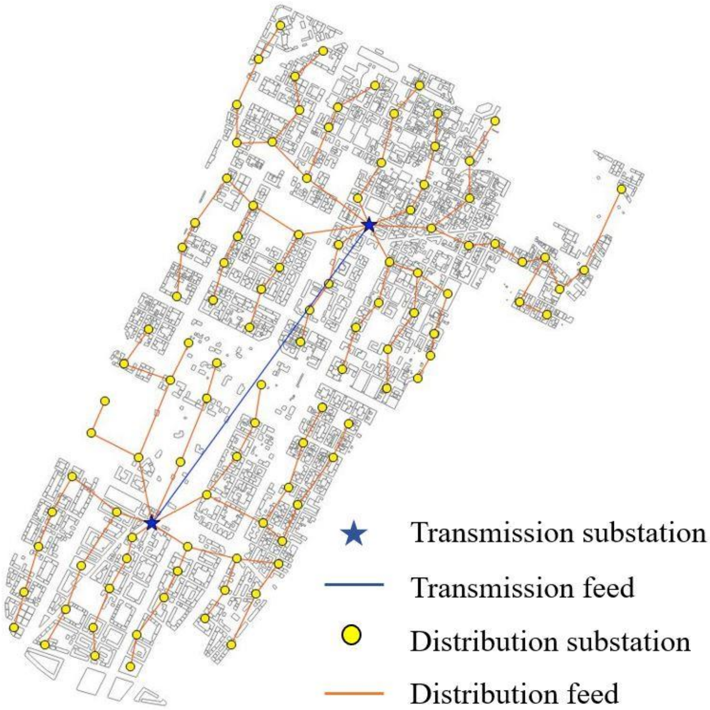

Figure 3-2. Power grid of neighborhood number 1.

Each neighborhood is modelled tailoring the involved parameters according to the specific designed area. **Figure 3-3** depicts the final map of the power distribution network for the Ideal City model. Each district has been assumed to have one HV-MV substation only and, when needed, a second central bus is installed as MV-LV.

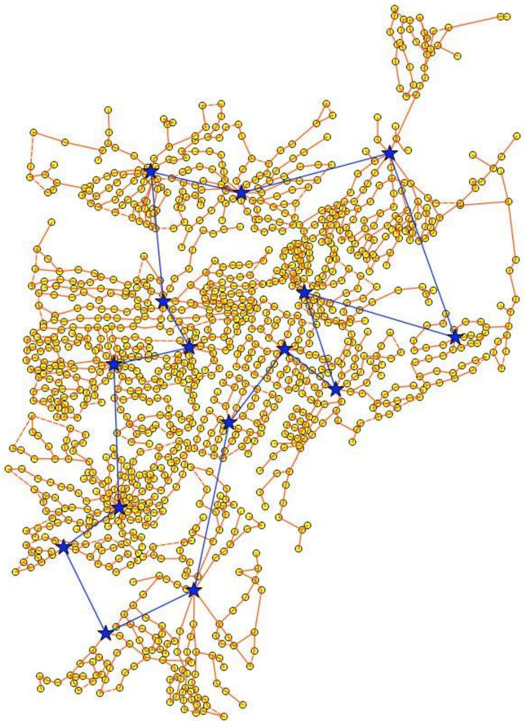

Figure 3-3. Power grid of Ideal City.

A comparison between the designed network and some real data obtained from one of the Turin's electricity suppliers has been performed. Table **4** reports the results of the comparison. The MV/LV data have been provided by the Turin Electric Company [35]. It can be seen that real data are similar to the results of the *Density Design Method*, which proves the effectiveness of the procedure. However, there are minor differences with respect to the real case due to the actual position of the MV/LV buses.

Parameters	**Real data**	**Simulation**
HV/MV buses	9	10
MV/LV buses	2,945	-
MV/LV residential buses (estimated)	1,090*	1,274

* In the U.S. the 37% of the electric power consumption is for residential purpose [36], so that value is used as reference to identify the target.

Table 4. Comparison between real data and simulation outputs.

4 RESILIENCE ASSESSMENT

Using the *Density Design Method* the power network of the entire virtual city is modelled. Each substation is assumed to supply only the closest buildings. The definition of the influence area of each substation is done through a QGIS tool. Given the information about the supplied electric power, it is possible to simulate a seismic scenario and analyze the effects on the power network.

The fragility of the network is evaluated within a city-scale approach. The assumption is the following: if the building where a substation is installed collapses, the grid components in that substation fail [37]. Therefore, the substations' fragility is linked to the buildings' one. Damages to the built environment are estimated using the procedure developed by Marasco et al. [16]. Under any given scenario, this methodology allows to evaluate the non-linear response of a multi-degree of freedom model for each building. Moreover, a Monte Carlo Simulation procedure is applied to consider the uncertainties related to geometry and mechanical properties [16; 17]. The seismic input used is the 6.5 M_w Norcia Earthquake that occurred in Central Italy in 2016, October 30. In **Figure 4-1** the buildings of neighborhood 1 which suffered "extensive" and "complete" damages after the earthquake simulation are highlighted in red.

Figure 4-1. Buildings severely damaged (in red) after the earthquake simulation.

The simulation outcomes identify different levels of damage to the built environment. When buildings in a "complete" and "extensive" damage state are identified, their hosted substations are considered failed. According to this criterion, 240 over 1274 substations failed after the applied scenario (**Figure 4-2**). At the end of the numerical simulation, 4815 buildings are no longer supplied, which corresponds to the 20.6% of the total.

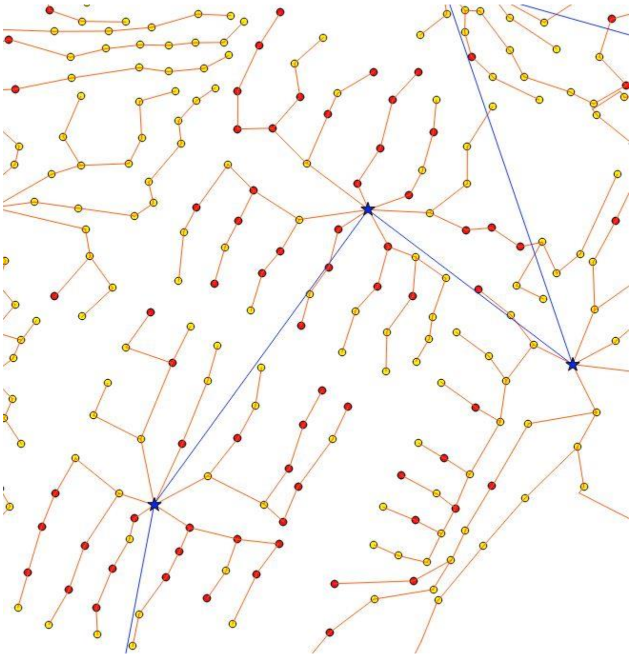

Figure 4-2. Substations damaged (in red) after the earthquake simulation.

The substations' recovery time is determined using either available data or considering only the transformers' recovery time, since these are assumed to be the main components [38]. A linear recovery function has been used to follow a conservative approach. Under this hypothesis, the *IRI* suggested by Italian Electric Power Authority is calculated using a return period (*TR*) of 50 years. **Figure 4-3** shows the variation of the index over the days after the seismic event considering 0 as the initial condition corresponding to full functionality. The event is considered to occur between day 1 and 2 of the simulation. After this time window, repair operations can start. Given its definition, the index focuses on the users left without electric power, which are 17,650 out of 960,500 inhabitants. The *IRI* curve highlights the long restoration time of the substations. Nevertheless, six days after the event, almost 50% of the grid is functioning again. However, the index does not give an idea of the severity of the power loss.

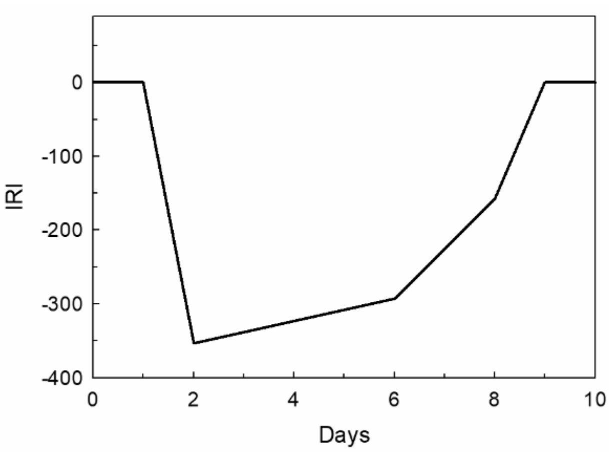

Figure 4-3. Risk Index (*IRI*).

Therefore, a second evaluation of the resilience is performed referring to the *ENS* (**Figure 4-4**). The *ENS* points out the energy that could not be delivered due to the damages suffered by the network. Analyzing the results, it can be stated that losses are relatively limited. This means that the power grid presents a good robustness, but the overall performance could be improved by increasing redundancy and resourcefulness. *IRI* is not able to highlight such resilience components, whereas *ENS* include these aspects, but is not able to represent the initial resilience condition of the network, as explained through the case study. In fact, the evaluation of the system resilience performed with the proposed *PRI* (**Figure 4-5**) highlights, at the time t=0, the intrinsic lower resilience of the power distribution network with respect to the optimal one (the network is not in full resilient conditions, indeed the first value is about 0.6). In this case, the T_{rr} parameter is equal to 0.57 because three classes of transformers are used; γ_{path} and PG are both assumed equal to 1.

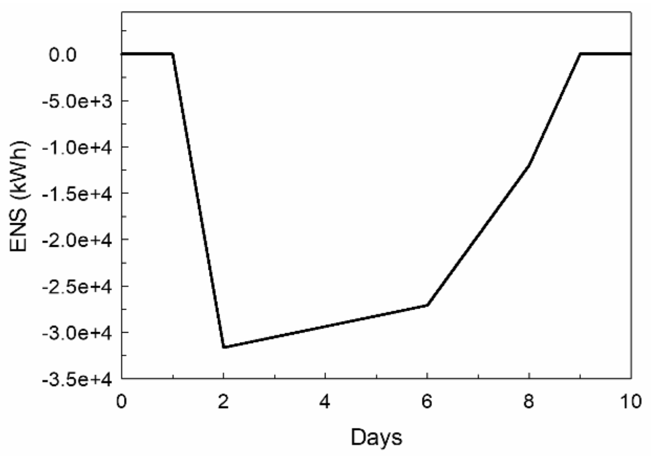

Figure 4-4. Energy Not Supplied (*ENS*).

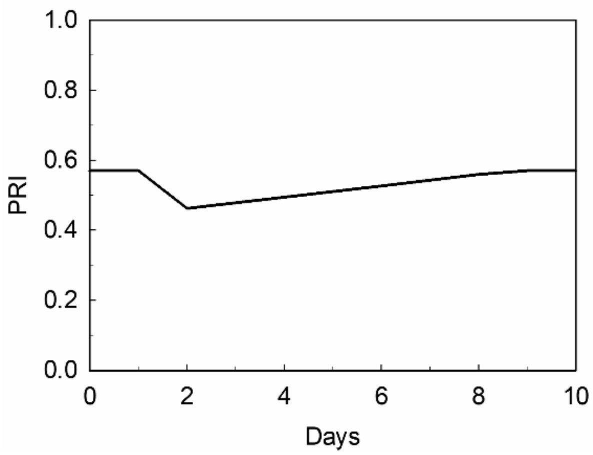

Figure 4-5. Proposed Power Resilience Index (*PRI*).

The *PRI* embodies the grid resilience and the graph in **Figure 4-5** illustrates the network functionality, according to the traditional definition [39]. The small drop immediately after the shock demonstrate a good resilience performance of the network, according to the selected parameters. The following smooth slope of the function is due to the repair time of multiple classes of transformers. The repair phase could be improved by acting on the *rapidity* component (T_{rr}) of resilience (i.e. by improving the preparedness and training). Therefore, the adoption of temporary solutions, such as alternative electric power paths and generators, should be considered in future studies.

Finally, an estimation of the repair cost of transformers was performed to give an idea of the direct non-structural economic losses [26]. The repair cost of different types of transformers was obtained using PACT, a FEMA tool to analyze the seismic performance assessment of structural and non-structural components [40] (**Figure 4-6**). Since data are given in US dollars (USD) they were converted in euros (€) assuming 1.2 as exchange rate. **Figure 4-7** summarizes the estimated cost to repair the damaged transformers within Ideal City.

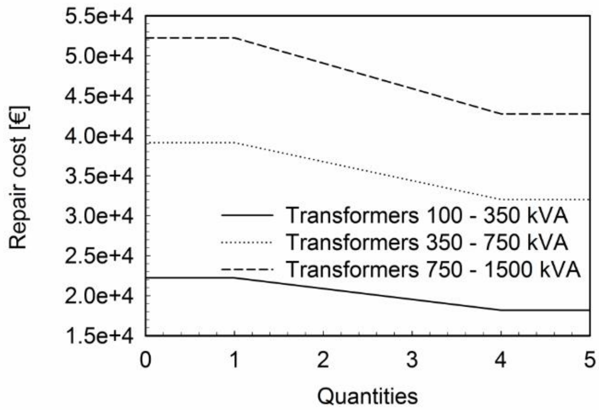

Figure 4-6. Repair cost of various types of transformers.

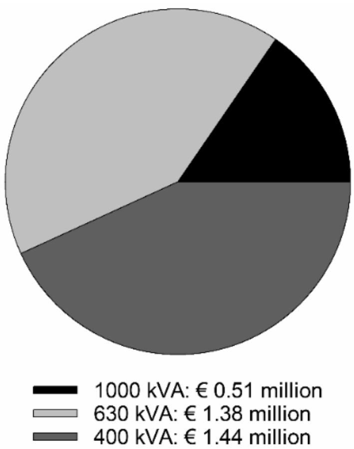

Figure 4-7. Transformers’ repair cost distribution.

5 CONCLUSIONS

In this paper, an integrated methodology consisting of two main components, namely the *Similarities Design Method* and the *Density Design Method*, is presented to assess the resilience of urban electric power distribution systems. It allows to perform resilience analyses depending on the available information of the built environment and can be applied to different case studies at the urban or even regional scale. The *Similarities Design Method* defines a compatible grid from a reliable database, considering exclusively the fragility of the electrical components. This tool can determine the general scheme of an urban distribution network and its intrinsic resilience. On the contrary, the herein proposed *Density Design Method* leads to a more realistic representation of an urban distribution grid considering also the interdependence with buildings. This methodology is applied to model the electric power distribution grid of Ideal City, a virtual large-scale city, by using population data and respecting the electric engineering constraints on the feeder's lengths and buses types. The two methods are complementary because the first one is more focused on the intrinsic fragility of the distribution system, while the novel one highlights the interdependency between the built environment and the installed electrical equipment.

Two resilience indices, the *IRI* and the *ENS* were computed. The analysis shows that the *ENS* index points out the economic losses in terms of power loss, while the *IRI* index is focused on the effects of the grid damage on the costumers. However, they do not directly incorporate in their formulation redundancy and resourcefulness. Therefore, the *PRI* is introduced. The *PRI* allows a comprehensive resilience assessment, where the effect of each resilience component (rapidity, robustness, redundancy and resourcefulness) can be determined. With respect to the results obtained in terms of *IRI* and *ENS*, the *PRI* highlights the importance of timely and fast repair operations to avoid huge non-structural economic losses. Furthermore, *PRI* is able to measure the initial resilience conditions of the network, which strictly depends on the types of equipment installed. Future research is aimed at introducing in the model temporary backup solutions and at evaluating also the structural economic losses.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] F. Cavalieri, P. Franchin, and P.E. Pinto, Fragility functions of electric power stations. In *SYNER-G: typology definition and fragility functions for physical elements at seismic risk*: Springer, 2014, pp. 157-185.

[2] FEMA, Multi-hazard loss estimation methodology, earthquake model, *Washington, DC, USA: Federal Emergency Management Agency* (2003).

[3] A. Navarro-Espinosa, Moreno, R., Lagos, T.,Ordonez, F., Sacaan, R., Rudnick, H., Improving distribution network resilience against earthquakes. In *IET International Conference on Resilience of Transmission and Distribution Networks (RTDN)*, Birmingham, UK, 2017.

[4] S. Lee, S. Hwang, M. Park, and H.-S. Lee, Damage Propagation from Component Level to System Level in the Electricity Sector, *Journal of Infrastructure Systems* 24 (2018):04018016.

[5] S. Giovinazzi, T. Wilson, C. Davis, D. Bristow, M. Gallagher, A. Schofield, M. Villemure, J. Eidinger, and A. Tang, Lifelines performance and management following the 22 February 2011 Christchurch earthquake, New Zealand: highlights of resilience, (2011).

[6] A. Mazza, Bompard, E., Chicco, G., Applications of power to gas technologies in emerging electrical systems, *Renewable and Sustainable Energy Reviews* 92 (2018):794-806.

[7] G.P. Cimellaro, *Urban Resilience for Emergency Response and Recovery. Fundamental Concepts and Applications*: Springer, 2016.

[8] I. Kongar, S. Esposito, and S. Giovinazzi, Post-earthquake assessment and management for infrastructure systems: learning from the Canterbury (New Zealand) and L'Aquila (Italy) earthquakes, *Bulletin of earthquake engineering* 15 (2017):589-620.

[9] V. Krishnamurthy, A. Kwasinski, and L. Duenas-Osorio, Comparison of power and telecommunications dependencies and interdependencies in the 2011 tohoku and 2010 maule earthquakes, *Journal of Infrastructure Systems* 22 (2016):04016013.

[10] C. Marnay, H. Aki, K. Hirose, A. Kwasinski, S. Ogura, and T. Shinji, Japan's pivot to resilience: how two microgrids fared after the 2011 earthquake, *IEEE Power and Energy Magazine* 13 (2015):44-57.

[11] D. Lee, and M.C. Constantinou, Combined horizontal–vertical seismic isolation system for high-voltage–power transformers: development, testing and validation, *Bulletin of earthquake engineering* 16 (2018):4273-4296.

[12] N. Romero, L.K. Nozick, I. Dobson, N. Xu, and D.A. Jones, Seismic retrofit for electric power systems, *Earthquake Spectra* 31 (2015):1157-1176.

[13] N. Romero, L.K. Nozick, I.D. Dobson, N. Xu, and D.A. Jones, Transmission and generation expansion to mitigate seismic risk, *IEEE Transactions on Power Systems* 28 (2013):3692-3701.

[14] S. Giovinazzi, M. Pollino, I. Kongar, T. Rossetto, E. Caiaffa, A. Di Pietro, L. La Porta, V. Rosato, and A. Tofani, Towards a decision support tool for assessing, managing and mitigating seismic risk of electric power networks. Paper read at International Conference on Computational Science and Its Applications. 2017.

[15] G.P. Cimellaro, Domaneschi, M., Mahin, S. & Scutiero, G. , Exploring simulation tools for urban seismic analysis and resilience assessment. 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering In *COMPDYN 2017*, Rhodes Island, Greece, 2017.

[16] S. Marasco, Noori, A.Z., Cimellaro, G.P., Resilience assessment for the built environment of a virtual city, *COMPDYN 2017 - Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* (2017):2043-2055.

[17] A. Zamani Noori, Marasco, S., Kammouh, O., Domaneschi, M. & Cimellaro, G.P., Smart cities to improve resilience of communities. In *SHMII-8 Conference*, Brisbane, 2017.

[18] J. Eidinger, Fragility of the Electric Power Grid. In *11th U.S. National Conference on Earthquake Engineering*, Los Angeles, California, 2018.

[19] S. Heunert, Koller, M., Huber, U., Heinz, K.,, Seismic Protective Measures for Electric Utilities in Switzerland - Implementation of the ESTI Guideline 248. In *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece, 2018.
[20] C. Kotanidis, Palaiochorinou, A., Koch, H.,, Overview of Major Seismic Standards for High Voltage Electrical Equipment. Proposal for Harmonization of IEC 62271-207 with IEEE 693. In *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece, 2018.
[21] Swiss Confederation, ESTI 248. Guideline: Earthquake Safety of Electrical Energy Distribution in Switzerland, 2015.
[22] IEEE Standards Association, IEEE 693 - IEEE Draft Recommended Practice for Seismic Design of Substations, (2018).
[23] S. Sordo, Domaneschi, M., Cimellaro, G.P., Mahin, S.,, Seismic Resilience of Electric Power Networks in Urban Areas. In *9th international conference on bridge maintenance, safety and management*, edited by F. Powers, Al-Mahaidi & Caprani, Melbourne, Australia: Taylor & Francis Group, 2018.
[24] The Italian National Authority for Electricity Gas Water and Wastes, Act March 7 2017 2/2017-DIEU, 2017.
[25] CEI, Standard EN 50341-2-13:2017, 2017.
[26] G.P. Cimellaro, ReinHorn, A.M., Bruneau, M., Framework for analytical quantification of disaster resilience, *Engineering Structures* 32 (2010):3639-3649.
[27] M. Bruneau, Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K.,, and W. Wallace, Winterfelt, DV., A framework to quantitatively assess and enhance the seismic resilience of communities, *Earthquake Spectra* 19 (2003):733-752.
[28] G. Prettico, Gangale, F., Mengolini, A., Lucas, A. & Fulli, G, Distribution System Operators Observatory: From Europe-an Electricity Distribution Systems to Representative Distri-bution Networks, Luxembourg: Publications Office of the European Union, 2016.
[29] C.M. Domingo, Román, T.G.S., Sánchez-Miralles, Á., Gonzá-lez, J.P.P. & Martínez, A.C., A reference network model for large-scale distribution planning with automatic street map generation, *IEEE Transaction on Power Systems* 26 (2011):190-197.
[30] MATLAB R2018a. The MathWorks, Inc., https://www.mathworks.com/.
[31] R.D. Zimmerman, Murillo-Sanchez, C. E. & Thomas, R. J., Matpower: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education, *IEEE Transactions on Power Systems* 26 (2011):12-19.
[32] Comune di Torino. *GEOPORTALE del Comune di Torino* 2018 [cited. Available from http://www.comune.torino.it/geoportale/.
[33] AutoCAD 2018. Autodesk, Inc., https://www.autodesk.com/.
[34] QGIS Las Palmas 2.18.19. Open Source Geospatial Foundation Project, https://qgis.org/en/site/.
[35] IRETI. *Rete e Impianti* 2016 [cited. Available from https://www.ireti.it/impianti.
[36] A.M. Salman. 2016. Risk-Based Assessment And Strengthening Of Electric Power, Michigan Technological University, Michigan.
[37] G. Celentano, Di Filippo, G.,, Behaviour of the Rieti power network during the August 24th, 2016 Earthquake. Paper read at Electrical grids Resilience, at Rome. 2017.
[38] FEMA, Provided Fragility Data. In *Seismic Performance Assessment of Buildings, Volume 3 - Supporting Electronic Materials and Background Docu-mentation*, edited by F. E. M. Agency, Washington, 2016.
[39] G.P. Cimellaro, Renschler, C., Reinhorn, A.M. & Arendt, L. , PEOPLES: a framework for evaluating resilience, *Journal of Structural Engineering* (2016).
[40] FEMA, PACT Performance Assessment Calculation Tool, Version 2.9.65, edited by F. E. M. Agency, Washington, 2016.