Towards a decision support tool for assessing, managing and mitigating seismic risk of electric power networks

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Abstract. Recent seismic event worldwide proved how fragile the electric power system can be to seismic events. Decision Support Systems (DSSs) could have a critical role in assessing the seismic risk of electric power networks and in enabling asset managers to test the effectiveness of alternative mitigation strategies and investments on resilience. This paper exemplifies the potentialities of CIPCast, a DSS recently created in the framework of the EU-funded project CIPRNet, to perform such tasks. CIPCast enables to perform risk assessment for Critical Infrastructures (CI) when subjected different natural hazards, including earthquakes. An ad-hoc customization of CIPCast for the seismic risk analysis and management of electric power networks is featured in this paper. The international literature describes effective and sound efforts towards the creation of software platforms and frameworks for the assessment of seismic risk of electric power networks. None of them, unfortunately, achieved the goal of creating a user-friendly and ready available DDS to be used by asset managers, local authorities and civil protection departments. Towards that and building on the international literature, the paper describes metrics and methods to be integrated within CIPCast for assessing the earthquake-induced physical and functional impacts of the electric power network at component and system level. The paper describes also how CIPCast can inform the service restoration process.

Keywords: Decision Support System (DSS), Damage Scenario, Seismic Risk, Electric Power system, Resilience, Decision Making Processes.

1 Introduction

Critical Infrastructures (CI) such as electrical grids, gas, water, telecommunication, roads, and railways networks are technological systems the correct functioning of which might impact on the life quality of citizens. CI protection is needed to guarantee the physical integrity of CI and the continuity of the services that they deliver. In particular, recent seismic event worldwide proved how fragile the electric power system can be to seismic events and similarly the critical importance of guaranteeing the functionality of the electric power service to support emergency management, recovery operations and the daily life of the affected communities. In the 1994 Northridge earthquake, for example, all of the Los Angeles Department of Water and Power's (LADWP's) 1.5 million power customers lost service, many for a week or more [1]. The 22nd February 2011 Christchurch, New Zealand, earthquake caused an estimated 629 million customer minutes of outages [2] that, in-turn, induced consequences on the functionality of the local telecommunication and waste networks. The impact could have been much worst. In fact, most of the power outages were caused by liquefaction damage to cables while above-ground components, including overhead lines and substations performed well, thanks to a seismic upgrade program that was implemented few years before the earthquake [3].

During the emergency and recovery phases, the local asset managers expressed the need and wish to perform scenario analysis [4] aiming to: compare alternative repair/reconstruction strategies; asses risks to mitigate risks, with a multi-hazard perspective; support the business case for investing into resilience. Decision Support Systems (DSSs) could have a critical role in assessing the seismic risk of electric power networks and in enabling asset managers to test the effectiveness of alternative mitigation strategies and to support business cases for investing into the resilience enhancement of the network.

The international literature describes effective and sound efforts towards the creation of software platforms and frameworks for the assessment of seismic risk of electric power networks. None of them, unfortunately, achieved the goal of creating a user-friendly and ready available DDS to be used by asset managers, local authorities and civil protection departments. Just to provide some examples (an exhaustive literature review is out of the scope of the paper) the American Lifeline Alliance, ALA, defined guidelines and accompanying commentaries [5] to provide a multilevel process by which the performance of electric power system in natural hazards and human threat events could be assessed. The HAZUS platform [6], developed in USA for estimating risks from natural hazards on the built-environment included: a) fragility curves for different components of electric power networks (i.e. substations, generation plants, and distribution circuits) giving the probability of reaching or exceeding four levels of damage, for a given level of ground motion; b) a simplified methodology for assessing the residual system performance in term of a probabilistic estimation of power outages; c) functionality restoration curves for electric substations and distribution circuits and for generation facilities, based on [7]. After that, an attempt to advance the modelling of the post-earthquake restoration processes for electric power networks was made by [8], that proposed discrete event simulation models to estimate geographically-disaggregated, quantitative restoration curves, including an explicit representations of the company's decision variables (e.g. repair crews and material available, etc.).

Finally, in Europe, the EU-funded Syner-G project, developed an integrated methodology and a software tool, referred to as OOFIM Object-Oriented Framework for Infrastructure Modelling and Simulation [9, 10] for the systemic seismic vulnerability and risk assessment of complex systems, including electric power networks. Syner-G compared and selected models for the seismic vulnerability assessment of electric power networks' components [11] and implemented the OOFIM tool on a real case study, namely the seismic probabilistic assessment of the functional performance (in terms of flows, connectivity loss and power loss) of the medium-high transmission network in Sicily region [12]. To achieve the goal of creating a user-friendly and ready available DSS to be used by Electric power network (EPN) asset managers, local authorities and civil protection departments, this paper proposes an ad-hoc customization of a recently created DSS, namely CIPCast, which enables to operationally perform risk prediction on Critical Infrastructures (CI) for different kind of natural hazards, including earthquakes. In particular, building on the available international literature, this paper proposes models and metrics to be integrated within the different functional blocks that constitute CIPCast (Fig. 1) to allow for the seismic risk analysis and management of electric power networks.

2 CIPCast Decision Support System

CI protection is a major issue for Nations, due to its transnational relevance. EU has thus issued directives to Member States in favour of an increased level of protection, recognizing the fact that CI constitute a unique, large system covering all the EU area [13]. In support of these EU directives, the APIC Lab[1] of ENEA has targeted the development and implementation of a DSS specific for CI protection, referred to as CIPCast. CIPCast was conceived and developed in the framework of two different projects, namely the EU-funded project "CIPRNet" (*Critical Infrastructures Preparedness and Resilience Research Network*) and the project "RoMA" (*Resilience enhancement of a Metropolitan Area*), funded by MIUR (the Italian Ministry of Research) as part of the research call "Smart Cities and Communities".

Making reference to simulated or real hazard scenarios, CIPCast DSS, can predict "*Damage Scenarios*" in term of punctual damages to the different CI components and "*Impact Scenarios*", where services outages induced by the physical damage to CI [14] components, are assessed at micro- (local scale) or meso- (regional scale) level. Finally CIPCast can estimate "*Consequences Scenarios*", starting from Impact Scenarios and via a consequences analysis, in term of estimated consequences on the affected communities (https://www.ciprnet.eu/ads.html).

CIPCast was conceived as a combination of free/open source software environments [15] including Geographic Information System, GIS features, which play a

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major role in the construction of such a tool. In the last few years, the geo-scientific community has been focusing on the use of GIS technologies and techniques for supporting natural disaster early warning and emergency management tasks. Multi-source data and GIS-integrated analysis can contribute to a better emergency planning, providing fundamental information for immediate response [16, 17]. The developed CIPCast DSS is capable to provide a user-friendly geographical user interface (GUI), by means of a specific WebGIS application, for querying and analysing geographic data and thematic maps, execute processes and simulations, produce and evaluate scenarios, etc. The creation of this information consultation tool, enriched by the geospatial component, implies the adoption of specific and suitable GIS and SDI (Spatial Data Infrastructures) architectures that have been developed using free/open source (FOSS) packages [18–20].

A specific Earthquake Simulator module for CIPCast (hereafter named CIPCast-ES) was developed and customised to assess the earthquake-induced damage to the building stock, at census tract and single building level, and the relative expected consequences on the residents in term of casualties and displaced population. CIPCast-ES allows working on a deterministic base, simulating damage and impact scenarios for selected earthquakes defined by the end-users, or for real events. In the first case CIPCast can support mitigation and preparedness planning; in the latter case CIPCast can inform emergency management allowing for testing alternative strategies and resource allocations. The possibility to account for the seismic microzonation (i.e. the possible amplification of the seismic hazard and therefore of the expected impacts due to soil conditions) was also included within CIPCast-ES, and was used for the case study of Florence Municipality, where a seismic microzonation study, providing the-specific amplification factor AF was provided [21].

3 Methods and Data

Different steps are necessary for estimating earthquake-induced damage, functional impacts and restoration timeframe for distributed infrastructures [22, 23], summarised below as:

1. *Hazard assessment*: generation of ground shaking and ground deformation maps and selection of the most appropriate earthquake hazard parameters to describe them;

2. *Classification of infrastructure components*: inventory and classification of the infrastructure components according to a defined taxonomy, so that the elements expected to behave similarly, by sustaining similar damages when subjected to an earthquake event, can be grouped together;

3. *Physical damage and functional impact metrics*: selection of appropriate scales for classifying earthquake induced physical damage to each component (e.g. for above-ground components: structural and non-structural damage to the building housing the component and damage to the equipment) and the residual operability of the component that do not necessarily correlate with the level and extent of the physical damage.

4. Damage assessment: identification of an appropriate hazard-damage relationship to be used for assigning a damage level/status (metrics in step 3) to each component identified and classified (step 2) as a function of the hazard estimated (as for step 1);

5. System performance assessment: estimation of the residual performance of the whole infrastructure accounting for the damages estimated at component level, via serviceability analysis and/or connectivity analysis; possibly adjust for interdependency effects from other systems;

6. *Service restoration assessment*: estimation of the repair and service restoration timeframe at both component and whole system level, based on empirical data/expert judgement and/or resource modelling.

Fig. 1 shows the main functional blocks (Bi) of CIPCast [24, 25] and the relevant components i.e. the Database and the Graphic User Interface (GUI). CIPCast block B1 gets external data from many different sources (e.g., seismic data), to establish the current external conditions. CIPCast B2 estimates the expected manifestation strength for predictable events. In B3 CIPCast elaborates a “Damage Scenario”, correlating the strength of the expected hazard manifestations with the vulnerability of the different CI elements in the affected areas, in order to estimate the probability that the manifestation could effectively damage (and, in the positive case, to what extent) the CI elements. B4 converts the damages expected for the CI elements into outages of the service. B5 is devoted to inform and support the response, by allowing testing and comparing different strategies for restoring the service by prioritising repairs and deploying physical and human resources.

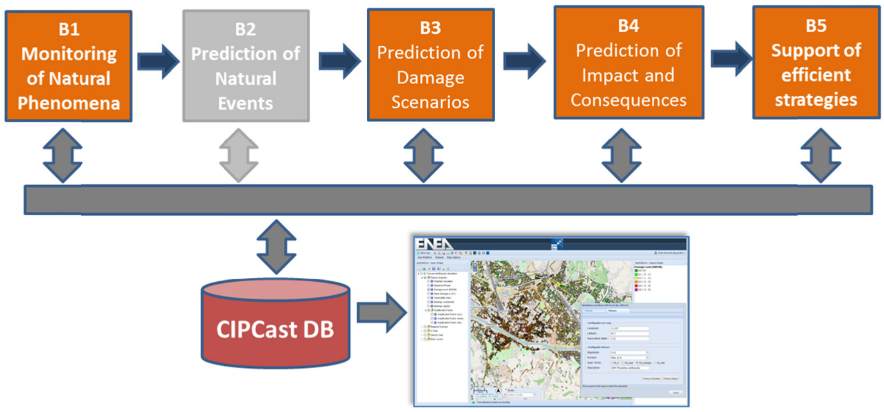

Fig. 1. CIPCast [25]: main functional blocks (Bi), Database and Graphic User Interface (GUI).

Table 1 summarises how the above-mentioned steps for estimating earthquake-induced risk to infrastructures should be customised for electric power networks and for implementation within CIPCast-ES and how they correlate with CIPCast functional blocks Bi (1-5). Steps 5 and 6 namely (Table 1) are already built into CIPCast. Further details are provided in the sub-sections below.

Table 1. CIPCast functional blocks and proposed steps for building capacity within CIPCast-ES for estimating earthquake-induced risk to electric power networks.

CIPCast functional blocks	CIPCast-ES – Electric power networks
B1	1. Seismic Hazard representation
B3	2. Classification of infrastructure
	3. Damage metrics at component level
	4. Damage assessment: physical and operational at component level
B4	5. System performance assessment*
B5	6. Service restoration assessment*

**Already built into CIPCast-ES*

3.1 Seismic Hazard representation

In order to evaluate the performance of a distributed infrastructure system after an earthquake, it is necessary to know the damage state and functionality at each component simultaneously and hence also the ground motion at each site simultaneously. A brief overview is provided on how to possibly assess and represent seismic hazard within CIP-Cast ES for distributed infrastructures, including: 1) description of the ground shaking in terms of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) at bedrock; 2) representation of amplification due to peculiar soil conditions; 3) estimation of ground deformation (PGD), and Liquefaction Potential Index, (LPI); 4) possible representation of uncertainties. A complete argument on the subject is out of the scope of the paper and can be found , e.g. in [26].

Description of ground shaking in term of PGA and PGV - CIPCast-ES allows the performance of deterministic seismic hazard analysis, for both real events and for end-user defined events. In the first case, and as far as the Italian territory is concerned, CIPCast-ES receives, within 1 min from the occurrence of the earthquake, the GPS coordinates of the earthquake epicentre, the hypocentre depth and the measured Moment Magnitude M_W (Richter scale) from the Italian National Institute of Geophysics and Volcanology, INGV, in Italy (http://cnt.rm.ingv.it/). A shake map is then generated using a suite of ground motion prediction equations (GMPEs). Currently CIPCast-ES implements Sabetta and Pugliese GMPE [27] in terms of PGA and different GMPEs in terms of Macroseismic Intensity I [21]. The seismic performance of above ground components of electric power networks, such as substations, can be assessed against PGA. However buried components such as cables would need to be assessed against Peak ground Velocity (PGV). Further attenuation laws will need to be included within CIPCast-ES to allow for that.

Representation of soil amplifications - After the prediction of the ground shaking either in term of PGA or PGV, possible site amplification due to soil condition would need to be accounted for. CIPCast-ES allows doing so, if a map of amplification factor AF (describing the ratio between the spectral acceleration Sa of the ground motion at the ground surface and at the bedrock) is provided. Further potentialities will be built within CIPCast-ES to allow for modelling site amplification directly within the selected GMPE itself, or simply by inputting the site class and/or a share wave velocity 0-30-meters depth (Vs30) value for each site in the ground motion field.

Estimation of PGD and LPI - The possibility to estimate PGD, conditional upon the intensity of the estimated ground shaking, should be also included within CIP-Cast-ES as PGD proved to be an issue for both above ground and buried components of electric power networks. Principal causes of PGD [28] will be estimated in CIP-Cast-ES as follow: a) coseismic fault displacement in the near-fault area will be calculated via semi-empirical correlations as a function of the earthquake magnitude (e.g. the ones available from Petersen et al., 2011); b) landslides triggered by seismic shaking [29] - this capability will be included in CIPCast-ES as discussed in the Conclusion section of this paper); c) liquefaction, lateral spreading, and seismic settlement will be estimated in term of liquefaction potential index (LPI) that proved to be a good predictor for the damages induced on buried cables [30].

Representation of uncertainties - GMPEs are derived empirically, further to the deterministic part, which calculates the median value of ground motion, GMPEs include random variables representing the variability that occurs within a single event (intra-event) and between separate events (inter-event) [31]. For analysis of spatially distributed systems the requirement for simultaneous ground motions at multiple sites means that the ground motions must be spatially correlated. For the sake of computational efficiency, straightforward approaches for obtaining correlated ground motion fields in CIPCast-ES, will be preferred to complex geostatistical methods [26].

3.2 Classification of infrastructure components

The purpose of classifying infrastructure into taxonomy is to group together elements that can be expected to behave similarly following an earthquake. Classification of infrastructure systems require firstly the identification of the different components included in the system and secondly the identification of the typologies/characteristics of the different components.

An electric power network may comprise different components: generation plants, substations and related sub-components, transmission lines (Table 2). Each of these serves a different function in the system. *Generation plants* are responsible for production of electric power; *transmission lines* transport the electricity from one location to another; *substations*, supply the power at load/consumer end. The sub-stations have different components, namely: *transformers* (usually step-down) to change the voltage level to a standard distribution level voltage; *feeders* connect the consumer/load end with the substation (with respect to a distribution system/substation); the terminal substation of each feeder ends with a *switch*. For each of the aforementioned components and sub-components there are different typologies, relating to structural or operational attributes. Transmission lines, for example, can vary based on their position (overhead lines or underground cables), their insulation material or their size. Substations may vary by load capacity or voltage[2]. Table 2 shows the assumed infra-

[2] Primary Substations (PS) contain High Voltage (HV) to Medium Voltage (MV) transformers; Secondary Substations (SS), Medium Voltage (MV) to Low Voltage (LV) transformers.

structure taxonomy for this work, their key constituent components and component attributes. The component attributes are the descriptors that could be used to group components into distinct typologies. Components can sometimes be pieces of equipment housed inside a building. In this case the attribute 'seismic design level' refers to whether the building is seismically designed or whether the component is anchored. Sometimes components are made up of a systemic arrangement of smaller sub-components. In this case 'seismic design level' refers to whether or not these sub-components are anchored.

Table 2. Example of infrastructure system taxonomy for electric power network.

<table>
<tr><th colspan="2">Components</th><th>Attributes</th><th>Graph</th><th>Damage Metric</th></tr>
<tr><td colspan="2">Generation plants</td><td>Capacity, seismic design level</td><td>Node</td><td>Damage level</td></tr>
<tr><td colspan="2">Substations</td><td>Voltage, seismic design level</td><td>Node</td><td>Damage level</td></tr>
<tr><td rowspan="2">Transmission Lines</td><td>Cables</td><td>Insulation Material, Cable material, Size</td><td>Edge</td><td>Repair Rate</td></tr>
<tr><td>Overhead Lines</td><td>Material</td><td>Edge</td><td>Repair rate</td></tr>
</table>

An inventory is an enumeration of the components and facilities in each of the typologies considered by the assumed taxonomy. Preparation of an inventory for infrastructure can be difficult since attributes cannot be identified by simple visual inspection and in many cases the components are not visible (e.g. buried lines). The inventory should therefore be prepared by collecting data from available sources. In the case of infrastructure however usually the only source is the system operator. To protect commercial interests and due to concerns over security, this type of information is not usually available in the public domain to a high level of detail and so depending on the granularity of the modelling exercise, it may be necessary to work in partnership with infrastructure owners [32]. It is quite critical to know the geographical location of each component. Availability of GIS layers of the entire network would be ideal: for instance, within CIPCast development, this has been possible in the framework of "RoMA" project, thanks to the partnership and cooperation of ACEA Distribuzione SpA – Areti, the major electrical distribution operator in Lazio Region (Italy).

3.3 Damage metrics at component level

The damage scales used to model infrastructure damage vary depending on the type of component being assessed. All networked infrastructures can be represented as an arrangement of 'point' components, also known as *nodes* and linear components, also known as *edges*, e.g. for an electric power transmission system represented diagrammatically as a network, the generation plant and substations are nodes and the overhead lines and buried cables are edges (Table 2).

Damage to infrastructure nodes can be described either in terms of physical damage or operational failure. Where components are housed inside buildings, it may be necessary to separately assess the operational state of the equipment and physical damage to the building. For infrastructure components housed in buildings, it is possible for the structure to be significantly damaged yet the component is fully operational as none of the equipment is damaged. Conversely, it is possible for the structure to be sound yet the component does not function because equipment inside has been damaged. The HAZUS methodology [6] considers both generation plants and substations (Table 3) as nodes of the electric power network classifying them in term of power output and voltage respectively and distinguishing, furthermore, whether or not their components are anchored (i.e. designed with special seismic tiedowns or tiebacks) or unanchored (i.e. designed according to normal requirements). Four damage states are defined for generation plants and substations, i.e.: slight/minor damage, moderate damage, extensive damage and complete damage (Table 3). In this application, the damage scale proposed for the building housing sub-stations is the 5 level damage scale defined by the European Macroseismic Scale, EMS-98 [33] already used by CIPCast-ES.

Table 3. Damage state definitions for substations (modified after [6])

Substations Sub-components	**Damage States**			
	Minor *	**Moderate**	**Extensive**	**Complete**
Disconnect switches	5%*	40%	70%	100%
Switches	5%	40%	70%	100%
Current transformers	-	40%	70%	100%
Transformers	-	-	70%	1000%
*Building***	D1-D2	D3	D4	D5

**"Failure of 5% of disconnect switches or failure of 5% of circuit breakers or building being in D1-D2 damage state"; **EMS-98 (Gruntal 1998) damage levels.*

While damage to infrastructure nodes is usually classified qualitatively, damage to infrastructure edges can be assessed quantitatively in term of repair rate. The repair rate, RR, is a deterministic calculation of the number of damages that a cable is expected to experience per unit of length, usually per kilometre. The relationship between repair rate and earthquake hazard commonly follows a power law or a linear relationship although more complex functions do exist. Most repair rate functions have been derived empirically. The typical form of a power law repair rate function is shown in Eq. 1, and a corresponding linear relationship is shown in Eq. 2:

$$RR = a \cdot IM^b \quad (1)$$

$$lnRR = c \cdot ln\mathrm{IM} + \mathrm{d} \quad (2)$$

where *RR* is the repair rate, *IM* is the earthquake hazard parameter and *a, b, c, d* are coefficients determined using some regression technique [34]. To account for different material properties or soil conditions, the repair rate function may include additional multiplying factors, which vary according to attribute, or a set of functions may be proposed for different conditions.

3.4 Damage assessment at component level

Fragility curves for generation plants and sub-stations. Fragility functions are used to evaluate earthquake-induced damage to generation plants and sub-stations of electric power network. For a given level of ground motion intensity, fragility functions determine the probability that a structure or component will be in, or exceeded, the i^{th} damage state, D_{si}. Fragility functions are often described by a lognormal probability distribution function as in Eq. 3, although it is noted that this distribution may not always be the best fit:

$$P_f\left(D_s \geq D_{s_i} \middle| IM\right) = \Phi\left[\frac{1}{\beta} \cdot \ln\left(\frac{IM}{IM_{mi}}\right)\right] \quad (3)$$

where Pf(·) indicates the probability of being at or exceeding a particular damage state, D_{si}, for a given seismic intensity level defined by an earthquake intensity measure, IM (e.g. PGA, PGV, PGD etc.), Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the earthquake intensity measure IM required to cause the i^{th} damage state and β is the total standard deviation. According to Eq. 3, fragility curves can be therefore drawn providing the values of the two parameters, IM_{mi} and β, as a function of IM. Cavalieri et al. [11, 35] provided an exhaustive overview on the main recent works on fragility functions for electric power system components along with the defining IM_{mi} and β parameters for each one of them. Table 4 provides, as an example IM_{mi} and β parameters for substations, as defined by HAZUS [6], making reference to empirical data/expert judgments and using Boolean logic and probabilistic combination of damage functions for jointly accounting for the performance of the constituting sub-components (listed in Table 3).

Differently from HAZUS, SYNER-G methodology [11] provides fragility functions for individual sub-components identifying all potential failure modes for the whole substation. As such, it is possible to determine the failure probability of the substation using fault tree analysis, where 'failure' refers to the substation's ability to distribute power rather than a physical damage state. SYNER-G fragility functions have been adapted from the work of Vanzi [36], specifically referring to Italian substations. Kongar et al. [32] reality-checked the reliability of both the aforementioned approaches comparing the damage predicted for substation with the ones observed after the Canterbury earthquake sequence 2010-2011. Both the approaches overestimated the damage and the loss of functionality. The adoption and implementation of either one or the other approach within CIPCast-ES will need to be carefully calibrated as discussed in the conclusions.

Repair rate relationship for buried cables. Kongar et al. [30] produced for the first time evidence-based repair rates for the prediction of damage to buried cables, processing and analysing the damaged caused to them by 2010-2011 Canterbury, New Zealand, earthquake sequence. The analysis showed that the fragility of buried cables is influenced more by liquefaction than by ground shaking, and that lateral spread can cause more damage than settlement alone. Kongar et al. [30] distinguished four different earthquake-induced geotechnical hazard zones (Table 4). Along with the typology of hazard and its intensity, the insulation material was identified as a critical factor influencing cable fragility. In Christchurch three materials were used for the insulation of 11 kV cables, namely: paper-insulated lead covered armoured (PILCA); cross-linked polyethylene (XLPE); and PILCA cables reinforced with high-density polyethylene (PILCA HDPE); plus some further unknown materials (Other). After the Canterbury earthquake sequence repair rates in PILCA cables resulted considerably higher than those observed in XLPE cables [30].

Table 4. Fragility function parameters for macro-components.

Damage State	Low Voltage				Medium voltage				High Voltage			
	U		A		U		A		U		A	
Slight /Minor	*IM**	*β*	*IM*	*β*	*IM*	*β*	*IM*	*β*	*IM*	*β*	*IM*	*β*
	0.13	0.65	0.15	0.70	0.10	0.60	0.15	0.60	0.09	0.50	0.11	0.50
Moderate	0.26	0.50	0.29	0.55	0.20	0.50	0.25	0.50	0.13	0.40	0.15	0.45
Extensive	0.34	0.40	0.45	0.45	0.30	0.40	0.35	0.40	0.17	0.35	0.20	0.35
Complete	0.74	0.40	0.9	0.45	0.50	0.40	0.70	0.40	0.38	0.35	0.47	0.40

**IM is IMmi as defined in Eq. 3, expressed in PGA[g]*
*** Low (34.5 kV to 150 kV), Medium (150 kV to 350 kV), High (350 kV and above)*

Conversely, Kongar et al. [30] analysis showed no trend between *cable age* and repair rates and a non-significant difference in repair rates for different *conducting materials* (conducting materials used in Christchurch included copper and aluminium). **Errore. L'origine riferimento non è stata trovata.** shows the repair rate function [30] that will be built into CIPCast-ES: repair rate functions refer to PILCA cables; coefficients are proposed to modify the 'base' PILCA functions for other materials. Therefore to estimate the repair rate for typologies, other than PILCA, one can calculate the repair rate for PILCA cables first and then multiply by the corresponding coefficient in Table 4.

Table 5. Repair rate function for PILCA cables, for different earthquake-induced geotechnical hazard zones, and coefficients for alternative insulation material typologies.

Earthquake-induced geotechnical hazard Zones	Repair Rate Function	Material dependant coefficient		
	PILCA	**XLPE**	**PILCA HDPE**	**Other**
A - No Liquefaction	- *	0.06	0.38	1.31
B - All Liquefaction	RR=4.317PGD-0.324	0.26	0.82	1.07
C - Liquefaction with settlement only	RR=1.23PGD	0.31	0.67	1.48
D - Liquefaction with lateral spreading	RR=7.951PGD+0.18	0.14	1.75	0.00

**No reliable relationship*

3.5 System performance assessment according to CIPCast-RecSIM

There are two paradigms for measuring system performance: connectivity analysis and serviceability analysis. Connectivity analysis determines whether two points in the system remain connected and as such can be used to determine whether a demand node (customer) remains connected to a source node. Serviceability analysis determines not just whether a customer is connected to a service but also what is the quality of that service. Possible serviceability metrics for electric power networks might include: power supply/demand ratio; voltage reduction. CIP-Cast ES can perform system performance assessment, thanks to a discrete-time event-based Java simulator, referred to as RecSIM [25], already built into built CIPCast B5 module (Fig. 1). By taking into account the predicted critical scenario, CIPCast-RecSIM can perform system performance assessment for a specific area of the electrical grid, both in term of connectivity and serviceability analysis (i.e. can map the evolution of the electric network in term of outages, after the damage and/or loss of functionality of some of the components). *"kilo-minutes of outages (kmin)"* is the reference key performance indicator (KPI) for the serviceability analysis within RECSIM, as this is a metric normally used by electrical operators, committed to provide, in the event of outages, the services back with a predefined Quality Level expressed in *kmin*:

$$kmin = \sum_{k=1}^{N} u_k T_k \quad (4)$$

where *kmin* is the sum of the products between the number of minutes of outages times Tk for each k^{th} substation; u_k is the number of electric customers fed by the k^{th} substation considered for the interval time of interest. According to the definition provided for *kmin* in Eq. 3 a short duration blackout in a highly populated area can produce a higher number of kilo-minutes of outages than longer outages in less populated areas. Fig. 2 reports an example of serviceability analysis carried out by means of CIPCast-RecSIM module. As a consequence of a simulated earthquake, inducing the failure of some components of the Medium Voltage (MV) power grid, *kmin,* for the census tracks (where costumers of the electric power system are located, represented as polygons) interested by the outages can be visualised in Fig. 2, where different colours (from green to red) represent different ranges of *kmin.*

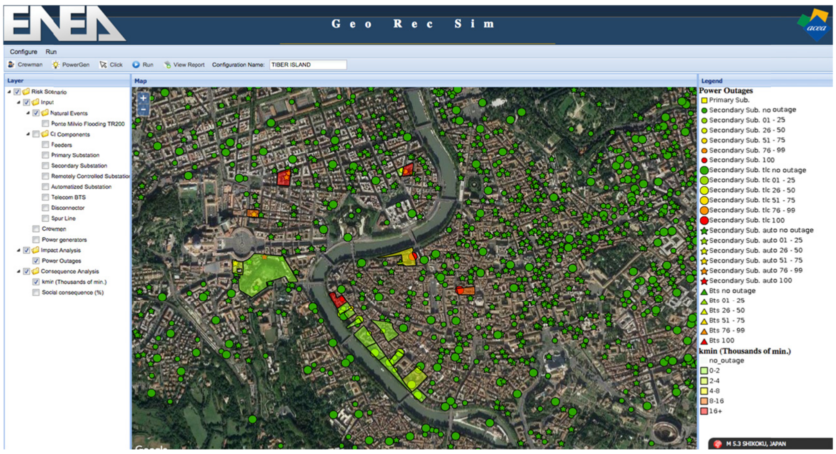

Fig. 2. CIPCast- RecSIM: example of geographical interface. Different colours (from green to red) represent different ranges of Quality Level expressed *kmin*

The "Consequences Analysis" module (see B4 in Fig. 1) can produce furthermore a more "societal-oriented" assessment of the impacts [37] by estimating the reduction of wellbeing for different societal sectors (e.g. citizens, economic activities, public services etc.) and the social and economic costs caused by the unavailability (or partial availability) of primary services such as electricity, telecommunications, drinkable water, mobility etc.. Further to the models already built into CIPCast-RecSIM for this societal-oriented impact assessment [25] other relationships will be added to assess the expected impacts on businesses of different industry sectors as a function of the outages duration for the electric power service [38].

3.6 CIPCast-RecSIM: Service restoration assessment

The purpose of restoration functions is to evaluate the time that it might take for damaged infrastructure components to be repaired based on their damage state and/or the average percentage of repairs that might take place within a specified time period [39]. Such functions may be derived empirically or estimated via resource modelling as a function of the available resources and work rate. CIPCast B5, by means of RecSIM, can evaluate the repair times at component-level and after that re-evaluate the system performance metrics at time-steps after the earthquake accounting for improved system conditions. Towards that CIPCast-RecSIM can simulate the basic functioning mechanisms of a switched and controllable electrical network, while accounting for the procedures usually performed in case of failure and the restoration functions for the different components, the number of emergency crews and power generators available to the electric operator. CIPCast B5 aims at informing CI operators and emergency managers on appropriate intervention, mitigation, and recovery strategies. At the current stage of development, the support actions are mainly related to the optimization of the system recovery sequence, in order to minimize the crisis impact on the continuity, measured in term of *kmin,* as defined in Eq. 3.

4 Conclusions

The paper demonstrated the feasibility and value of developing an ad-hoc DSS for assessing and mitigating the seismic risk to electric power network. The authors are collaboratively working on the steps described in the paper and on testing the reliability of the proposed models on real cases in Europe, including the recent earthquake sequence in Central Italy, where the network data are available thanks to the cooperation of ACEA. The CIPCast-ES will allow end-users to perform the assessment of possible earthquake-induced impacts on the overall system (accounting also for interdependencies) [40] and to estimate the possible consequences on citizens and on environment, starting from both real data (acquired by distributed sensors and monitoring networks), and from the elaboration of simulated scenarios.

As future developments, CIPCast will be further enhanced with additional functionality, primarily the use of Earth Observation data to improve the territorial analysis, particularly considering the landslide risk [29]. Secondly the integration of additional data for environmental monitoring, and finally the capability of collecting crowdsourced data (e.g., real-time road traffic conditions), allowing the citizens to provide useful information to be exploited by the Public Authorities for improving the situational awareness in Metropolitan areas. In turn, the availability of a huge amount of data stored and processed within CIPCast will allow the Authorities to provide to the CP, the CI Operators and the citizens effective information in real time, therefore improving the decision processes for crisis and emergencies management.

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