Received: 8 July 2020 | Accepted: 26 July 2020
DOI: 10.1111/1468-5973.12309

ORIGINAL ARTICLE

WILEY

A comprehensive system for semantic spatiotemporal assessment of risk in urban areas

Alex Coletti[1] | **Antonio De Nicola**[2,3] | **Antonio Di Pietro**[2,3] | **Luigi La Porta**[2,3] | **Maurizio Pollino**[2,3] | **Vittorio Rosato**[2,3] | **Giordano Vicoli**[2,3] | **Maria Luisa Villani**[2,3]

[1]Booz Allen Hamilton, Lanham, MD, USA
[2]ENEA, CR Casaccia, Rome, Italy
[3]European Infrastructure Simulation and Analysis Centre, Italian Node (EISAC.it), Rome, Italy

Correspondence
Maria Luisa Villani, ENEA, CR Casaccia, Via Anguillarese 301, 00123, Rome, Italy.
Email: marialuisa.villani@enea.it

Funding information
project ARCH ("Advancing Resilience of Historic Areas against Climate-related and other Hazards"): This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 820999 project RAFAEL ("System for Risk Analysis and Forecast for Critical Infrastructure in the ApenninEs dorsaL Regions"), Grant/Award Number: PON MIUR ARS01_00305; project RoMA ("Resilience enhancement of Metropolitan Area"), Grant/Award Number: PON MIUR SCN_00064

Abstract

Risk assessment of urban areas aims at limiting the impact of harmful events by increasing awareness of their possible consequences. *Qualitative* risk assessment allows to figure out possible risk situations and to prioritize them, whereas *quantitative* risk assessment is devoted to measuring risks from data, in order to improve preparedness in case of crisis situations. We propose an automatic approach to comprehensive risk assessment. This leverages on a semantic and spatiotemporal representation of knowledge of the urban area and relies on a software system including: a knowledge base; two components for quantitative and qualitative risk assessments, respectively; and a WebGIS interface. The knowledge base consists of the TERMINUS domain ontology, to represent urban knowledge, and of a geo-referenced database, including geographical, environmental and urban data as well as temporal data related to the levels of operation of city services. CIPcast DSS is the component devoted to quantitative risk assessment, and WS-CREAM is the component supporting qualitative risk assessment based on computational creativity techniques. Two case studies concerning the city of Rome (Italy) show how this approach can be used in a real scenario for crisis preparedness. Finally, we discuss issues related to plausibility of risks and objectivity of their assessment.

KEYWORDS
computational creativity, conceptual modelling, geographic information system, ontology, risk assessment, temporal database

1 | INTRODUCTION

Improving preparedness to crisis due, for instance, to extreme events as natural phenomena like earthquakes and flood, will increase city resilience. However, this requires to analyse and to prioritize a multitude of relevant scenarios that could happen in a typical risk assessment activity. Current literature distinguishes between *qualitative* risk assessment, performed by stakeholders to identify a limited number of possible risk situations worthy of consideration, and *quantitative* risk assessment, performed by analysts to estimate the impact of predefined risks by means of mathematical risk functions, simulation or assimilation of historical data. Estimation of cascading failure propagation in electric power systems (Baldick et al., 2008; Pahwa et al., 2014) and losses due to an earthquake (Silva et al., 2014) are examples of works on *quantitative* risk assessment. However, most of the existing approaches do not consider the temporal evolution of the state of the systems under assessment and, consequently, how the risk level could change over time. Furthermore, as the qualitative assessment usually relies on human judgment and experience, it is almost impossible to identify unlikely but disruptive risks that, due to communication gaps, remain uncovered. These unexpected risks are recently referred to as "black swans" (Taleb, 2010).

Here, we propose a comprehensive approach that encompasses *qualitative* and *quantitative* risk assessment and allows generating geo-localized risk mini-models dynamically associated with sensitive points of interest (POIs). Examples of points of interests are hospitals, transportation services, museums and restaurants. In general, risk mini-models are fragments of conceptual models representing possible risks of socio-technical systems (Coletti et al., 2017). Risk mini-models related to a specific POI could change over time. For instance, the level of risk for a metro station could vary according to the time of the day (e.g. from very high level during the rush hour to low level during closing times). By ingesting temporal data on the level of operability of urban services, we compute dynamically the level of risk of all the automatically generated risk mini-models.

Furthermore, by exploiting computational creativity techniques, this approach overcomes limitations of existing qualitative risk assessment approaches, as they only rely on past data and on the experience and the different perception of experts. Computational creativity is a new field of Artificial Intelligence devoted to defining computational systems that create artefacts and ideas (Colton & Wiggins, 2012). We refer these methods to the creative process of the experts while they are conceiving risks that could lead to possible disruptive crisis situations that never happened in the past. In a recent paper (De Nicola et al., 2019), the authors explicitly validated the effectiveness of a computational creativity approach in supporting emergency management officers and risk analysts to conceive novel emergency scenarios for smart cities. In this work, more generally, the focus is on the capability of an automatic approach to supply risk descriptions that are useful to experts in their activity of qualitative risk assessment. These risks may represent both familiar and new plausible situations for the selected areas.

The approach is supported by a software system that allows the above-mentioned dynamic generation of geo-localized risk mini-models. The system consists of the following components: a knowledge base including TERMINUS (TERritorial Management and INfrastructures ontology for institutional and industrial Usage; Coletti et al., 2019), a domain ontology formalizing knowledge concerning environment, city services and infrastructures and related risks, and a geo-database including data on urban areas and how they vary in time; WS-CREAM, a web service built on top of CREAM (CREAtivity Machine; De Nicola et al., 2019), implementing the computational support for automatic risk identification and ranking, by querying the ontology and using context data; and CIPCast (Giovinazzi et al., 2017), a GIS (geographic information system)-based tool for risk analysis of critical infrastructures, enhanced with forecasting and decision support functionalities. Preliminary results, discussed in Barcaroli et al. (2019), are here extended by considering the temporal dimension of risk assessment.

TERMINUS was built by means of *ontology design patterns*. An *ontology design pattern* is a reusable conceptual structure to support the ontology engineering process (Gangemi & Presutti, 2009). This is used by WS-CREAM to run semantic queries automatically built from pre-specified ontology patterns.

We present our experience on comprehensive risk assessment on two case studies regarding relevant areas of the city of Rome (Italy). The first case study considers the area close to Isola Tiberina, which is located in the city centre and encompasses a large museum, shops, restaurants and hospitals. As it is close to the Tevere river, we associated this use case to the flood risk. The second use case encompasses Sapienza University, its General Hospital "Policlinico Umberto I," some offices and a metro station. For this area, we have considered risk related to earthquakes.

We discuss plausibility and objectivity issues related to risk assessment processes. The paper has been organized as follows. Section 2 presents relevant work. The literature review was mainly conducted in the research areas concerning both quantitative and qualitative risk assessment. Section 3 describes the ideas behind qualitative and quantitative risk assessment. The proposed software system is described in Section 4. Section 5 describes the experimentation of the approach in the city of Rome. Finally, the last section presents conclusions.

2 | RELATED WORK

This paper deals with dynamic risk assessment for metropolitan areas due to natural events. The most common approaches to this purpose are either *quantitative* or *qualitative* risk assessment.

Among the existing works on *quantitative* risk assessment for populated areas, we cite the seismic vulnerability and risk assessment (Vicente, Parodi, Lagomarsino, Varum, & Silva, 2011) for the city of Coimbra in Portugal; the earthquake risk assessment for Istanbul metropolitan area (Erdik et al., 2003); and the *quantitative* risk assessment from climate change (World Health Organization, 2014) that, among the different causes of death, includes also costal flood mortality.

In the scope of qualitative risk assessment, among the most important contributions are the paper of Rinaldi, Peerenboom, and Kelly (2001) that discusses types of risks due to interdependencies of critical infrastructures, the paper of Coletti, De Nicola, and Villani (2016), presenting a semantic model for system-of-systems risks and discussing water systems risks with roots on climate change hazards, and the paper of Lückerath et al. (2018), within the EU project "Climate Resilient Cities and Infrastructures—RESIN," that, similarly, presents a modelling approach to cause–effect relationships underlying risks and vulnerabilities. Both works propose conceptual modelling approaches for vulnerability assessment of urban areas. These identify some upper level concepts as hazard, exposure and impact that should drive adaptation strategies due to climate change. The paper of Dierich, Tzavella, Setiadi, Fekete, and Neisser

(2019) proposes an approach mixing qualitative and quantitative risk assessment. With respect to these works where qualitative assessment is performed by interviewing experts, our proposed activity is automatized by means of semantics-based and computational creativity techniques.

Support tools for qualitative risk assessment, finalized to decision-making for resilient cities, include the Quick Risk Estimation (QRE) tool of the United Nations Office for Disaster Risk Reduction (UNDRR), developed with the support of the European Commission under the Sendai Framework and freely available since October 2019.[1] This tool, which is based on MS Excel, is aimed to help city authorities and other stakeholders in the common understanding of current and future risks to assets of cities. These users are guided in manually scoring likelihood of threats and rating exposure, vulnerability and response measures on assets in a 5-point Likert scale (Likert, 1932). Based on these data, the QRE tool computes a compound risk level by means of a risk matrix. In our approach for risk assessment, not only risks are automatically assessed by means of a similar risk matrix and same computation methods, but we also automatize the scoring of the individual risk parameters based on real data, as explained in Section 4, so avoiding error-proneness of human-based data entry and subjectivity of the scoring.

Various initiatives in the literature are devoted to building ontologies for risk assessment. One of the first was the vulnerability upper model (VUM) and a VUM ontology, presented by Coletti et al. (2016), including concepts as risk, threat, system, stakeholder, severity and vulnerability. Then, this ontology was extended to build the first version of the TERMINUS ontology presented in Coletti et al. (2019). After these, other initiatives include the common ontology of value and risk presented by Sales et al. (2018) and the ontology of emergency managing and planning about hazard crisis presented by Gaur, Shekarpour, Gyrard, and Sheth (2018). Other ontologies refer to close domains as the ontology proposed by Elmhadhbi, Karray, and Archimède (2019) that covers disaster management and the related operational emergency response system. TERMINUS was used as it focuses on the knowledge required in this paper, which concerns territory, risk and crisis management. Furthermore, it is structured as a multi-level specialization hierarchy that is a feature required in order to use the computational creativity functionalities of WS-CREAM effectively (De Nicola et al., 2019).

Currently, the TERMINUS ontology used in this work covers physical and functional vulnerabilities of infrastructures and urban services to describe risks in a urban area. In future works, we plan to extend it with psychological vulnerabilities of people for a more detailed account for human aspects in the description and assessment of risks. Among such type of studies, the paper by Hayes, Blashki, Wiseman, Burke, and Reifels (2018) investigates impacts of climate change hazards on human health, including emotional resilience and psychosocial wellbeing, whereas the paper by Teffali, Matta, and Chatelet (2019) analyses predictability of the stress influence in the management of a crisis.

Recent works address the problem of spatiotemporal assessment of risks either from a quantitative perspective (Zhu et al., 2019) or by simulating cascades of faults (Grafenauer, König, Rass, & Schauer, 2018; König & Schauer, 2019) due to critical infrastructure interdependencies. In Zhu et al. (2019), the spatiotemporal distribution of flooding is simulated by using the LISFLOOD-FP model and the spatial movements of residents are simulated during the urban flooding time period. Instead, in Grafenauer et al. (2018) and König and Schauer (2019), the possible status of localized critical infrastructures is computed over an entire time period by means of a software based on a time-dependent Markov chain model. Again, with respect to them, none of these approaches uses semantic technologies to automatize the risk assessment process. However, in the case of operational scenarios management, tools based on semantic technologies exist and are presently under advanced testing (e.g. see Greuel, Denker, & Myers, 2017).

Adopting creativity approaches for serious purposes is currently one of the aims of the open innovation (Chesbrough, 2003) community. For instance, Zachos, Maiden, and Levis (2015) present a creative approach to open innovation for health and safety in manufacturing plants. With respect to them, we adopt semantic query processing to support this creative process. Finally, Zanni-Merk, Cavallucci, and Rousselot (2009) propose a creative approach for knowledge acquisition to support innovation. We share with them the use of an ontology but we propose different reasoning techniques and a different application scenario.

3 | FOUNDATIONAL ASPECTS OF SEMANTIC SPATIOTEMPORAL ASSESSMENT OF URBAN RISKS

In this section, we present the foundational aspects of the proposed approach for risk assessment.

A risk mini-model is defined by a set of concepts representing a risk situation from a semantic perspective. This set includes a service (s), a vulnerability (v), a critical event (c) and the hazard (h) causing it. The formal definition of the *risk mini-model r* is the following:

$$r = \{s, v, c, h\} \text{ with } s \in S,\ v \in V,\ c \in C, \text{ and } h \in H.$$

A geographical area could include one or more POIs. For the sake of simplicity, we consider a POI as a system providing a service. For instance, we consider a metro station from the perspective of service that can be provided to commuters. Other perspectives for a system are, for instance, the economic value and the physical infrastructure. A detailed discussion on system aspects can be found in Coletti et al. (2019). Given a POI, a *geo-localized temporal risk mini-model* can be considered as an instance of a risk mini-model that represents a POI, its semantic functional representation, a vulnerability, a critical event and the hazard causing it, the geographical coordinates of the POI, and the time of the critical event. Hence the geo-localized temporal risk mini-model r_p is defined as follows:

$$r_p = \{r, p, x_i, t\},$$

where p represents the POI, x_i are the spatial coordinates ($i = 1,2,3$) of the POI, and t is the time.

Then, we define the *RiskLevel* mapping function that maps the domain of the geo-localized temporal risk mini-models to the level of risk:

$$RiskLevel: \{r_p\} \rightarrow \mathcal{L}$$

where

$$\mathcal{L} = \{\text{Very High, High, Medium, Low, Very Low}\}.$$

A detailed treatment on how the *RiskLevel* mapping function is computed is presented in Section 4.

Finally, we define the semantic spatiotemporal risk space as the set of all the pairs consisting of a geo-localized temporal risk mini-model and its corresponding risk level:

$$\mathcal{R}_p = \{(r_p, l)\}.$$

Figure 1 depicts as coloured circles some geo-localized temporal risk mini-models for an urban area. Colours represent the level of risk in a given instant of time (red: high, yellow: medium, green: low). As it can be deduced from the figure, the level of risk of a geo-localized temporal risk mini-models can change over time.

According to our approach, a risk analyst selects a POI included in a urban area. Then, for that POI he/she automatically retrieves a ranked list of possible geo-localized temporal risk mini-models. Finally, he/she selects one of them to observe its level of risk and its temporal evolution over time.

4 | SOFTWARE SYSTEM FOR QUALITATIVE SEMANTIC SPATIOTEMPORAL ASSESSMENT OF RISKS

The automatic approach for semantic spatiotemporal risk assessment enhances the decision support system capabilities of a pre-existing GIS-based system devoted to Critical Infrastructures (CI) protection (Giovinazzi et al., 2017). A view of the overall system architecture is in Figure 2, showing the functional blocks to enable risk assessment following both quantitative and qualitative methods, and the data and domain knowledge they use. More specifically, the overall system consists of independent services exposing the required functions for risk assessment to a middle layer, which is responsible for their coordination and of their interaction with the components of the knowledge base. A WebGIS interface is used to both activate some of the system functions and to query GIS data from a map.

The quantitative risk assessment services in Figure 2 realize a decision support system named CIPCast, conceived and designed in the framework of a EU-funded project CIPRNet *Critical Infrastructures Preparedness and Resilience Research Network* (www.ciprnet.eu), and further developed in subsequent research projects and activities (project RoMA and RAFAEL, funded by the Italian Ministry of Education, University and Research). Instead, the semantic qualitative risk assessment services rely on a domain-specific configuration of the CREAtivity Machine Web Service (WS-CREAM) (De Nicola et al., 2019) by means of the TERMINUS ontology, representing knowledge related to hazards, systems and emergency management. A more detailed description of the system functions follows.

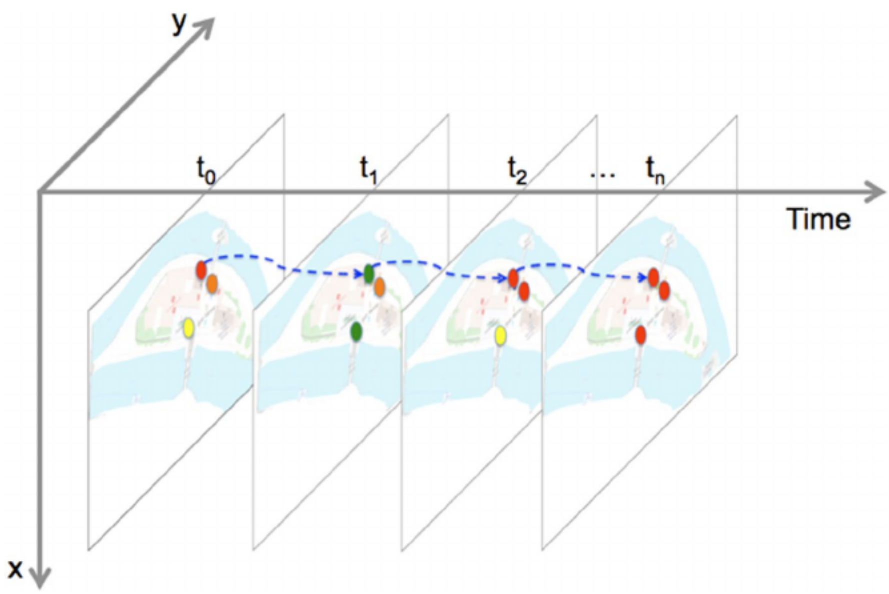

FIGURE 1 Evolution of level of risk of a geo-localized temporal risk mini-model [Colour figure can be viewed at wileyonlinelibrary.com]

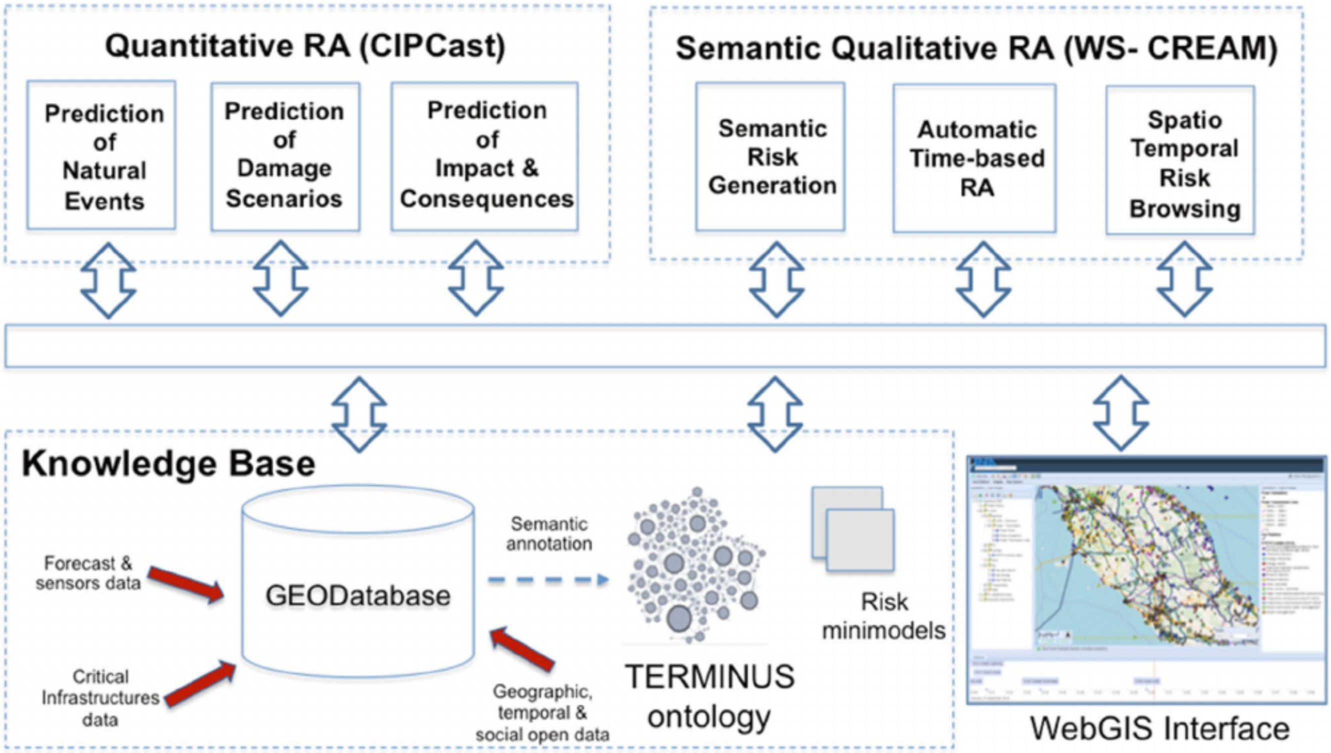

FIGURE 2 Semantic spatiotemporal system architecture [Colour figure can be viewed at wileyonlinelibrary.com]

4.1 | CIPCast functionality for quantitative risk assessment

CIPCast Decision Support System (DSS) is conceived as a combination of free/open-source software environments that includes GIS features to perform operational risk prediction and analysis of critical infrastructure for natural hazards such as earthquakes. Indeed, multisource data and GIS-integrated analysis contribute to a better emergency planning, providing fundamental information for immediate response. All data and information available to such a purpose, such as base cartography, risk maps, critical infrastructure features data, data from sensors, scenario produced are stored and managed in a PostGIS-based geo-database. A specific component is devoted to dynamically acquiring external data from many different sources (e.g. weather and seismic data stations), to establish the current external conditions. These data are used to implement the following functional blocks for quantitative risk assessment.

- *Prediction of Natural Events*, by estimating the expected manifestation strength for predictable events in the areas under observation;
- *Prediction of Damage Scenarios*, by correlating the strength of the expected hazard manifestations to the *specific* vulnerability (i.e. that related to the perturbing event) of the different critical infrastructure (CI) components located in the affected area. The damage scenarios are performed for all the CI components having a high probability of being damaged due to the hazardous event(s).
- *Prediction of Impacts and Consequences*, by combining (a) damages expected for the CI components (e.g. the breakage of a transformer in an electric substation); (b) topological and behaviour features of the network; and (c) network (inter-)dependencies, in order to estimate over time the degradation of the service(s) level provided by the network(s) (e.g. an electric outage caused by a failed substation).

CIPCast can exploit different types of data, both from its own GIS database (geo-database) and from external repositories. In particular, the geo-database contains several data features: (a) territorial and environmental data (basic cartography, hydrogeological data, morphology, geology, etc.); (b) socio-economic data (census data); (c) data about structures (features and characteristics of buildings) and infrastructures (power lines, gas pipelines, water supply network, telco network components, roads and railways, etc.); (d) natural hazard and risk maps (earthquake catalog, seismic risk, inventory of landslides, flood risk, etc.); and (e) point of interest (POI) data. In order to predict the damage scenario, CIPCast gathers real-time data from field sensors and from external repositories/services. In particular, it acquires (a) earthquake events from the seismic network of the Italian institute for geophysical studies (INGV); (b) weather data and forecast from meteorological models (CETEMPS) and services, reporting data on rainfall, temperature, humidity, wind, pressure, etc. in a given area; and (c) satellite remote sensing data (e.g. measurements of displacement through SAR data).

Risk assessment functions of CIPCast concern physical damages estimations on buildings and components of critical infrastructures.

Given the geographic location of specific elements (e.g. critical infrastructures and POI), CIPCast can assess—for each element—the possible degree of damage depending on the type of event expected (and its intensity), taking into account the vulnerability of the element itself to a specific hazard (such as earthquake and flood) (Taraglio et al., 2019). Then, in the case of critical infrastructures, CIPCast evaluates the impact that the expected service damages could cause on the affected infrastructure element (e.g. substation, powerline and pipeline) and, consequently, on the entire infrastructure (Di Pietro et al., 2016).

Furthermore, a specific seismic risk module has been realized, which operates as a stress tester enabling to simulate earthquakes and assessing the resulting chain of events (Matassoni et al., 2017). Such CIPCast module firstly simulates the ground shake map (related to earthquake intensity), by also considering the amplification effects, and then estimates the expected damages to buildings and other infrastructure elements. It allows to:

- Simulate earthquake events (synthetic or by reproducing past events actually occurred) and estimate the (deterministic) scenarios in terms of macroseismic intensity;
- Estimate damages on buildings and infrastructures, whose vulnerability was previously estimated;
- Estimate consequences on population (casualties, people to be evacuated) and on the delivery of services (e.g. buildings collapse and consequence on roads).

Additionally, some decision-making support is provided to operational processes such as multiple strategies to manage crisis scenarios. Figure 3 presents a screenshot of the CIPCast interface showing the level of damage for buildings in a large area affected by a simulated earthquake.

4.2 | WS-CREAM functionality for semantic qualitative risk assessment

The automatic functions for semantic spatiotemporal risk generation and assessment aim at supporting a user, such as a risk analyst or a city planner, to imagine possible scenarios and identify relevant ones for objectives such as city emergency management and/or risks mitigation. Indeed, this component provides an automatic ranking of the generated situations, based on context information on spatiotemporal dimensions, a useful function to speed up the subsequent qualitative assessment activity by the user.

These functions rely on spatiotemporal context data; a domain ontology for territorial management and infrastructures; and a risk

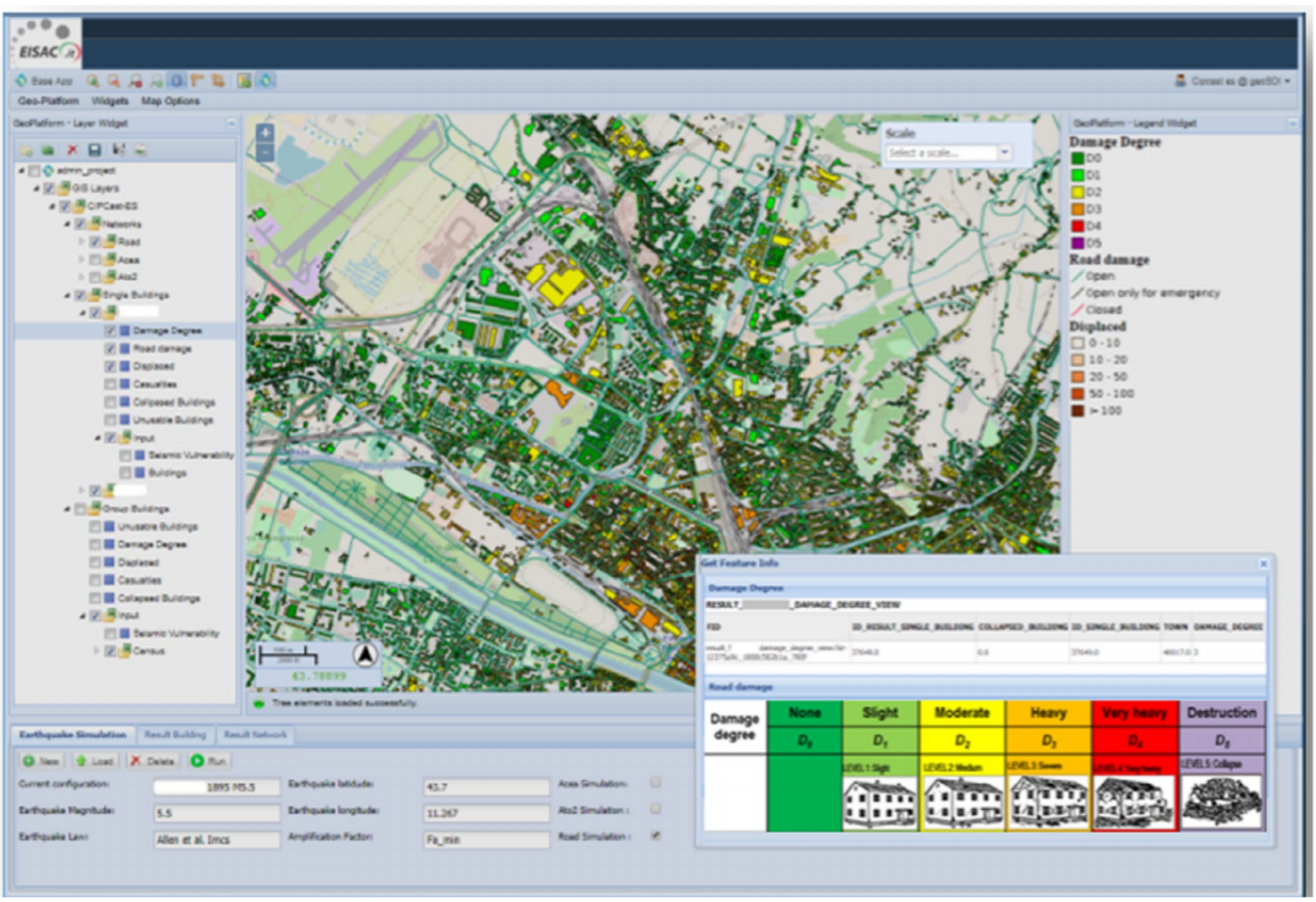

FIGURE 3 Level of damage for buildings in a large area affected by a simulated earthquake [Colour figure can be viewed at wileyonlinelibrary.com]

assessment function. The context data are supplied by the GIS database, the domain ontology used by this system is TERMINUS (Barcaroli et al., 2019), and the risk assessment function, which can be specified in a configuration file, consists of a risk matrix accounting for hazard—damage levels, evaluated on a psychometric Likert scale for questionnaires (Likert, 1932). A detailed description of TERMINUS and the semantic spatiotemporal qualitative risk assessment functions follows.

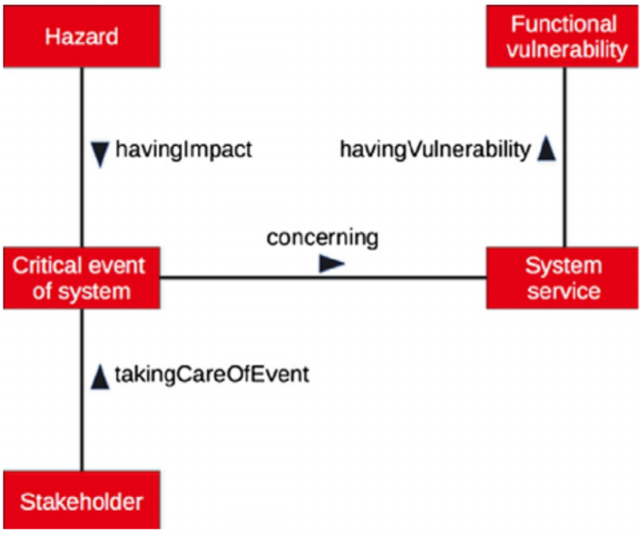

FIGURE 4 UML representation of the design pattern to model risks for system service [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | TERMINUS: An Ontology for Territorial Management and Infrastructures

TERMINUS is a domain ontology that includes semantic representations of environment, critical infrastructures and related hazards, risks and threats. An ontology is a formal specification of a shared conceptualization (Gruber, 1993; Borst, 1997). It defines concepts, relationships and axioms relevant for representing a domain of interest. TERMINUS has been engineered by considering real (historical) situations and by extending some ontology design patterns. At the current stage, TERMINUS has been built by deriving concepts from the vulnerability upper model (VUM) design pattern (Coletti et al., 2016), from the system aspect design pattern presented by Coletti et al. (2019) and from the risk of system service design pattern (Barcaroli et al., 2019) that is presented in the following. TERMINUS also includes knowledge related to interdependencies between critical infrastructures (Rinaldi et al., 2001). In particular, the risk of system service design pattern allows representing risks for city services due to catastrophic events as earthquakes, floods and landslides. This ontology design pattern is depicted in Figure 4. It consists of five upper level concepts: Hazard, Critical_event_of_system, Functional_vulnerability, System_service and Stakeholder. The description of these five upper level concepts is presented in Table 1, whereas the description of the relationships between them is presented in Table 2.

Finally, Figure 5 depicts an excerpt from TERMINUS ontology showing a fragment of the taxonomy related to the Critical_event_of_system concept.

TABLE 1 Description of the five upper level concepts belonging to the *risk of system service* ontology design pattern

Concept name	Description
Hazard	Event or trend or their impacts (e.g. floods, droughts and sea level rise) with likely detrimental consequences to human systems (adapted from Hazard concept as described by Mora et al., 2018)
Critical_event_of_system	Event representing one or more effects on systems from exposure to a hazard; effects are mediated by the strength of the hazard and the vulnerability of the exposed system (Adapted from the Impact concept as described by Mora et al. (2018))
Functional_vulnerability	The propensity of a system function to be adversely affected. This results from the balance between sensitivity and adaptive capacity (adapted from the Vulnerability as described by Mora et al. (2018))
System_service	Service provided by system
Stakeholder	A person or organization that is interested in a system or its subsystems

TABLE 2 Description of the relationships between concepts belonging to the *risk of system service* ontology design pattern

Object property name	Description
havingImpact	Conceptual relationship between a Hazard and a Critical_event_of_system
concerning	Conceptual relationship between a Critical_event_of_system and one of its provided services (i.e. System_service)
havingVulnerability	Conceptual relationship between System_service and one of its function vulnerabilities (i.e. Functional_vulnerability)
takingCareOfEvent	Conceptual relationship between Stakeholder of a system and Critical_event_of_system

4.4 | Semantic risk generation

This function takes as input a list of service types, semantically annotated with TERMINUS concepts, which are present in a user selected urban area, and the type of hazard with its associated properties. Semantic annotation was done manually by some experts knowing the addressed geographical area. A SPARQL query (Coletti et al., 2017) is automatically built from the predefined ontology pattern, as that derived by the conceptual model in Figure 4. Such pattern is addressed in the configuration file, and the query is run on the TERMINUS ontology to retrieve a list of semantic descriptions of possible service risks. These are represented as records of the following table.

$$\left[\begin{array}{c}\text{System service, Hazard, Functional vulnerability,} \\ \text{Critical event of system, Stakeholder}\end{array}\right] \tag{1}$$

These records are built with concepts of TERMINUS, where the System_service component specifies the type of service among those provided as input, and, possibly, the Hazard component specifies the type of the hazard chosen by the user.

4.5 | Automatic time-based risk assessment

This function implements risk ranking mechanisms accounting for both semantic criteria and for contextual information related to the characteristics of the POI and of the geographical area where it operates. Specifically, all entities of the risk mini-model, except the Stakeholder whose role is limited to risk description and understanding, are associated with one or more metrics, which are either evaluated at conceptual level, or at instance level. Then, the overall risk is assessed, by aggregating these values according to a time-dependent formula that can be configured for the system. The entity-level metrics are defined as described in Table 3, and they are individually assessed by some experts in the system preparation phase. Indeed, these values depend on geographical and environmental information, on the specific city, on the service types and on risk expert's knowledge, and they can be updated during system operation following the changes at the information sources.

During a risk assessment activity, a predefined risk formula:

$$\mathit{RiskLevel}(\text{POI, RM}, x_i, t) := \mathit{RiskLevel}\left(\text{POI, RM}, \left[\text{SV, TR, VL, CL, HR}\right]\right) \tag{2}$$

is applied to every POI, risk mini-model RM, geographical position of the POI x_i and the time t. This formula aims at assigning a time-dependent risk level to each risk mini-model of a POI of the city. Essentially, a risk level indicates the importance of the identified risk, so it serves the purposes for comparing risks with other risks of the same POI. One approach, commonly used in qualitative risk assessment, is to combine risk levels with a risk matrix, a two-dimensional table for combining likelihood of hazard and severity of impact on a system. For the application presented in this paper, the risk matrix is shown in Figure 6, and it is very similar to the matrix proposed by the United Nations Office for Disaster Risk Reduction. The severity level of a risk mini-model for a POI is computed as the *geometric mean* of the values: SV, TR, VL and CL in (2), and the likelihood ranking is provided by official studies from environmental institutions.

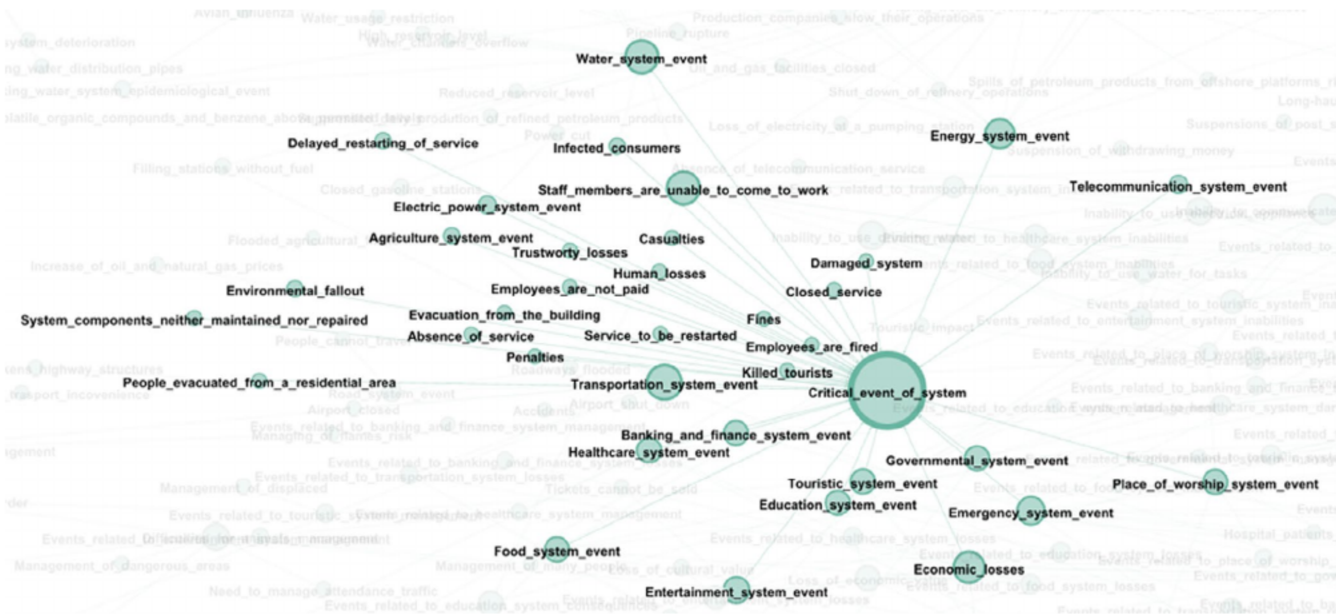

FIGURE 5 Excerpt from TERMINUS ontology with a fragment of the taxonomy related to the Critical_event_of_system concept [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Risk assessment metrics

Entity	Metric	Input	Description
System service	*ServiceValue* (SV)	POIName	*Aim*: instance-level metric applied to a POI, indicating the relative value and/ or criticality of the specific service within the city, that is compared to other services. Hence, this metric provides a measure of a possible loss, functional, economic or quantity of victims, in case of adverse events *Value:* expressed in a Likert scale *Data source*: Rome municipality
	TimeRelevance (TR)	POIName	*Aim*: instance-level metric applied to a POI, indicating the level of operation of the service at the time of occurrence of an adverse event. Hence, this metric provides a time-related weight for the possible consequent loss, functional, economic or quantity of victims, for the given POI *Value*: expressed in a Likert scale *Data source*: operation time profile of the service (e.g opening–closing time and number of visits throughout operation), available from Google information service
Vulnerability	*VulnerabilityLevel* (VL)	Functional Vulnerability	*Aim*: conceptual level metric associated with a specific functional vulnerability type of a service, indicating the relative importance of that vulnerability *Value*: expressed in a Likert scale, specified in the ontology as attribute of the given Functional_Vulnerability entity *Data source*: domain expert's knowledge
Critical event of system	*ConsequenceLevel* (CL)	CriticalEvent	*Aim*: conceptual level metric associated with a specific type of critical event (e.g. loss) that may occur at a service after an adverse event, indicating its relative importance for the service *Value*: expressed in a Likert scale, specified in the ontology as attribute of the given type of Critical_Event_Of_System entity *Data source*: domain experts' knowledge
Hazard	*HazardRiskLevel* (HR)	Hazard, POIPosition	*Aim*: instance-level metric associated with a type of hazard and the geographical position of the specific POI, indicating the probability of occurrence of that hazard in the locality of the POI *Value*: expressed in a Likert scale, which is defined for each type of hazard *Data source*: ISPRA, institution devoted to environmental studies in Italy (http://www.isprambiente.gov.it)

4.6 | Spatiotemporal risk browsing

Once the risk mini-models are ranked by the automatic time-based risk assessment component, various types of browsing functionality can be implemented, according to the spatiotemporal dimension or risk relevance values. An example of result visualization of risk mini-models based on time and risk relevance is shown in Figure 7.

4.7 | Usage scenario of the overall system

One of the envisaged usages of the overall system is in the *prevention phase* from potential crisis events that pose risks to a specific urban area. The following scenario illustrates such a use case.

> A risk analyst wants to assess the consequences of an earthquake for a zone of an urban area. The analyst specifies the hazard and selects the city area by interacting with a map by means of the WebGIS interface of the system. Relevant geographic information for that area includes points of interests such as schools, hospitals, public places, and CI components such as water pipes, road characteristics and position of electric substations.
>
> Two types of studies are currently supported by the system, namely (i) damage estimation on buildings and infrastructure components of the area by means of simulation models and (ii) initial qualitative multi-perspective assessment of risks for the POIs of the area and consequences for citizens. Whereas the first type of analysis may be completely automatic as it relies on full availability of the required data, the second type is a machine assisted human activity, as complete information is hardly available and requires elicitation of tacit knowledge from several experts.
>
> For the second type of study, the entities within the selected area by the analyst are automatically identified and this information exploited to generate semantic descriptions of possible risk scenarios. The results are supplied to the risk analyst on the WebGIS interface. The analyst is also supported by the system

		Severity Level				
		Very Low	Low	Medium	High	Very High
Likelihood	Very Low	Very Low	Very Low	Low	Medium	Medium
	Low	Very Low	Low	Medium	Medium	Medium
	Medium	Low	Medium	Medium	Medium	High
	High	Medium	Medium	Medium	High	Very High
	Very High	Medium	Medium	High	Very High	Very High

FIGURE 6 Risk matrix [Colour figure can be viewed at wileyonlinelibrary.com]

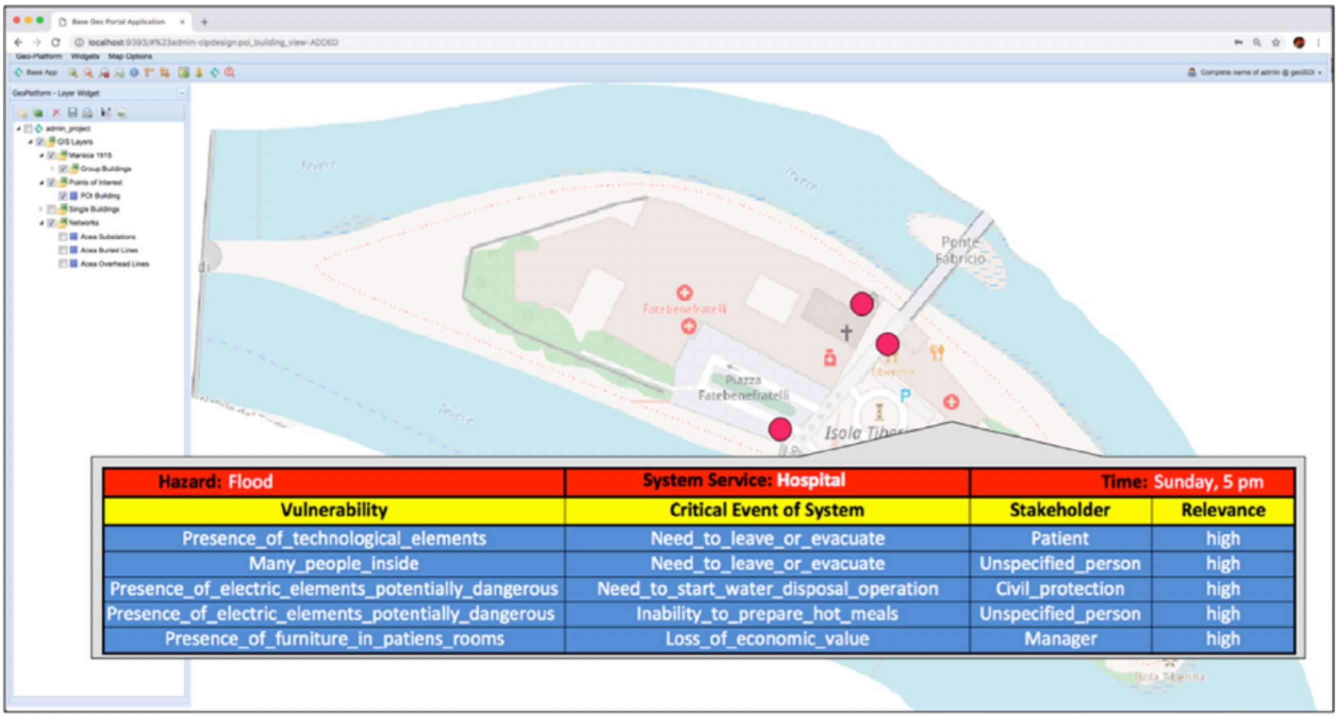

FIGURE 7 Example of result visualization of risk mini-models based on time and risk relevance [Colour figure can be viewed at wileyonlinelibrary.com]

in the identification and browsing of all relevant risk situations, with the final aim to improve completeness, and hence reliability, of the assessment.

5 | CASE STUDY: RISK ASSESSMENT IN ROME (ITALY)

We identified two urban areas in Rome (Italy) and used context GIS-based data for an empirical study with the objective of evaluating effectiveness and usefulness of the proposed semantic spatiotemporal risk assessment approach. In particular, we intended to investigate the support, given by our system, to a risk analyst and/or a city emergency operator to identify risk situations and evaluate their priority in order to handle them.

To this purpose, we set the following research questions.

(RQ1) To what extent the semantic risk descriptions generated by the system are plausible?

(RQ2) To what extent the system is useful for risk assessment?

A detailed description of the performed experimentation follows.

5.1 | System set-up

The selected areas for the study are General Hospital "Policlinico Umberto I" and Isola Tiberina. We selected the first area (Policlinico) for the case study because this area is highly crowded due to the presence of the largest Rome University (Sapienza University), one of the largest university in Europe with over 110 000 students, a large hospital (with availability of 1,200 beds), several public and private services, restaurants, a metro service and an historical cemetery. A map of this area including some relevant POIs is depicted in

Figure 8. For this case study, we would like to investigate the possible risks due to the impact of an earthquake on such a crowded area. The second selected area, the Isola Tiberina area, has been considered as it includes another important hospital in Rome, museums, restaurants and governmental offices. This area is also close to the Tevere river and, as such, it is exposed to flood risk, whose possible impacts we aim at investigating. A map of this area with some relevant POIs is reported in Figure 9.

An example of assessment of a semantic spatiotemporal risk mini-model related to the Isola Tiberina area is presented in Table 4.

The following activities were required to configure the system and prepare the queries for the experiment.

1. *Specification of the hazard event*. As above-mentioned, risks from an earthquake event were required for the Isola Tiberina area and from a flood event for the Policlinico area.
2. *POIs identification and selection*. Two subsets of POIs located in the two selected areas were chosen according to the following criteria: (a) each subset must include relevant POIs for the city; (b) the two subsets include POIs of the same service type; and (c) each subset contains POIs of various types. So, for Policlinico area, the POIs included in Table 5 were chosen. Instead, for Isola Tiberina area, the selected POIs are reported in Table 6.
3. *Selection of temporal data*. Two different week days/time were decided for the assessment of the risks from the hazard events. Namely, Sunday at 11:00 and Tuesday at 21:00 were chosen for Isola Tiberina, instead Sunday at 21:00 and Tuesday at 18:00 were decided for Policlinico. Furthermore, the service levels of the individual POIs of the areas were set correspondingly. Concerning Isola Tiberina, Sunday at 11:00 a.m. was chosen because we assumed that there are several people in the POIs of the area on that day and at that time. Instead, we assumed that there are relatively few people on Tuesday at 21:00. Concerning Policlinico, Sunday at 21:00 am was chosen because we assumed that there are few people in most of the POIs of the area (except the selected restaurant) on that day and at that time. Instead, we assumed that there are relatively more people on Tuesday at 18:00 as hospital and metro station are expected to be crowded.

5.2 | Experiment

The semantic risk mini-models generation and qualitative spatiotemporal risk assessment functions run on the areas and temporal based input sets described above. Then, four risk assessment experts, with good knowledge of Rome geographical and urban characteristics, were asked to estimate the quality of the obtained results. In particular, two of them, *expert A* and *expert M*, analysed the risk assessment lists for the POIs in the Policlinico under an earthquake hazard, and the other two, *expert G* and *expert V*, analysed the risks for the POIs in the Isola Tiberina area under a flood

FIGURE 8 Policlinico area and related POIs [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 9 Isola Tiberina area and related POIs [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Isola Tiberina risk mini-model

Functional_vulnerability: People_inside
System_service: Pharmacy
Critical_event_of_system: Health_and_physical_consequences
Stakeholder: Patient
Hazard: Flood
POI name: Farmacia Ospedale Fatebenefratelli
Risk level on Sunday at 11:00: very high
Risk level on Tuesday at 21:00: high

TABLE 5 POIs selected for the Policlinico area scenario

POIName	Type
Cimitero Monumentale del Verano	Cemetery
Ambasciata presso la Santa Sede Ungheria	Embassy
Istituto Superiore di Sanità	Office
Policlinico	Hospital
Police Station	Police
Ufficio Postale Roma 62	Office
Ristorante La Casetta Snc	Restaurant
Policlinico metro station	Station
Sapienza University	University

TABLE 6 POIs selected for the case study related to Isola Tiberina area

POIName	Type
Farmacia Ospedale Fatebenefratelli	Pharmacy
Ospedale Fatebenefratelli	Hospital
Musei Capitolini	Museum
Santa Maria in Cosmedin	Worship place

event. Each expert was asked (a) to judge the plausibility of the generated risk mini-models with a yes/no answer; (b) to evaluate on the basis of a three-level Likert scale their relevance for each corresponding POIs on the map. After the assessment, each expert was asked to provide the criteria followed for attribution of the risk level, by weighting from 0 to 5 the following aspects: *Hazard localization*, that is hazard risk level for the POI localization; *Economic value*, that is the relevance of the POI in the city; *Vulnerability*, that is the type of vulnerability supplied in the risk mini-model; *Critical event*, that is the type of impact supplied in the risk mini-model; and *Time*, that is the time indicated for the hazard event. The obtained risk evaluations and comparison with the system results are reported in Tables 7 and 8. Furthermore, Table 9 summarizes the accordance of the risk results by each expert with those by the system, and Figure 10 the accordance of the experts on the risk evaluation criteria, compared with that used by the system.

TABLE 7 Plausibility of the risk mini-models for the POIs of the two areas according to the experts

Area	Time		Plausible RMM	Not plausible RMM	Percentage plausible	Percentage not plausible	Not plausible (shared)	Percentage not plausible (shared)
Policlinico	18:00 Tuesday	Expert A	392	71	84.67%	15.33%	49	10.58%
	21:00 Sunday	Expert M	253	210	54.64%	45.36%		
Isola Tiberina	21:00 Tuesday	Expert G	290	12	96.02%	3.98%	0	0%
	11:00 Sunday	Expert V	302	0	100%	0%		

TABLE 8 Comparison of the qualitative risk assessment by the system with that by the experts

	High relevant RMM	High relevant RMM (SYSTEM)	Medium relevant RMM	Medium relevant RMM (SYSTEM)	Low relevant RMM	Low relevant RMM (SYSTEM)
Expert A						
#	79	0	139	345	245	118
%	17.06%	0%	30.02%	74.51%	52.92%	25.49%
Expert M						
#	51	0	100	305	312	158
%	11.02%	0%	21.60%	65.87%	67.39%	34.13%
Expert G						
#	7	180	45	29	295	138
%	2.02%	51.87%	12.97%	8.36%	85.01%	39.77%
Expert V						
#	81	206	173	6	93	135
%	23.34%	59.37%	49.86%	1.73%	26.80%	38.90%

TABLE 9 Analysis of agreement in relevance level assessment between experts and WS-CREAM

	Number of mini-models evaluated as WS-CREAM	Percentage of mini-models evaluated as WS-CREAM	Number of mini-models evaluated differently by WS-CREAM	Number of mini-models evaluated differently by WS-CREAM
Expert A	186	40.17%	277	59.83%
Expert M	199	42.98%	264	57.02%
Expert G	134	38.62%	213	61.38%
Expert V	89	25.65%	258	74.35%

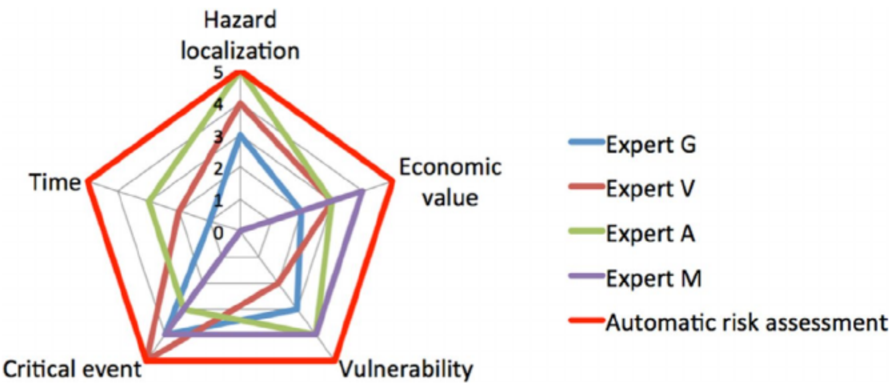

FIGURE 10 Spider graph of expert weighting factors [Colour figure can be viewed at wileyonlinelibrary.com]

5.3 | Answers to the research questions

RQ1 concerns validation of the automatically generated risk mini-models by the experts. As shown in Table 7, all the risk descriptions for the POIs of Isola Tiberina were judged plausible by the assigned experts and about 90% of the risk descriptions for the POIs in the Policlinico area were judged plausible by both *expert A* and *expert M*, who evaluated them. This is a very good result, which is also related with the quality of the source ontology and appropriateness of the risk semantic model.

RQ2 is concerned with evaluation of the automatic support to the qualitative risk assessment process. Especially in the case of less familiar risk descriptions, as in the case of our risk mini-models, this process is human-based. Therefore, we used this trial to measure differences (if any) in the human perceptions of risk situations, even when performed by domain experts, and an automatic assessment leveraging on an urban risk knowledge base, environmental risk data and a type of risk formula as in the common practice for qualitative risk assessment. In this respect, for each area, in Table 8 we reported the number of risk mini-models judged of low, medium or high relevance by each of the two evaluators for each POI, and compared with the results by the system. From the data in Table 8, we noticed that the expert results generally differ from the system results, and that, for both areas, results by the two experts also differ. Table 9 presents the detailed analysis of agreement in relevance level assessment between experts and the system (WS-CREAM). This shows the number of risk mini-models that were judged at the same level of relevance. Also, this analysis confirms the need of an objective means to assess the relevance.

A reason for these differences can be found in Figure 10, showing that the four experts have actually attributed different weights to the five parameters of the risk formula computed by the system. This result confirms that *subjectivity* is an influencing factor in *qualitative* risk assessment and that an automatic support in the activity of risk quantification may be useful to provide an objective perspective as a basis for an experience-based qualitative risk assessment process, required whenever data for simulation-based risk prediction is not available and to identify new plausible risks. This conclusion was also confirmed by a direct feedback received from the experts.

6 | CONCLUSIONS

Risk assessment of urban areas is a complex activity due to uncertainties on hazards, on the variety and the temporal behaviour of systems. We presented a comprehensive software system devoted to risk assessment, including a novel component aiming to provide descriptions of relevant risk situations in an urban area, especially useful when *qualitative* risk assessment is required. This is achieved by using semantic reasoning on a domain ontology and automatically measuring the level of the generated risks. The presented system relies on data of the geographical areas, the societal and infrastructural characteristics of the urban services under analysis and also the temporal evolution of such characteristics. The system integrates WS-CREAM, a software application based on semantic and computational creativity techniques, with CIPCast, which is a GIS-based DSS for risk analysis of critical infrastructure, boosted by forecasting capabilities and some optimization functionalities for the identification of optimal strategies to recover from specific critical infrastructure outages. We presented how these two systems can operate in synergy to perform semantic spatiotemporal risk assessment for urban areas, and provide validation results of the approach on two case studies within the city of Rome. Validation has been performed by involving experts with experience in real past situations. The results demonstrate that the generated risk mini-models are generally plausible and the automatic evaluation is useful to provide an objective input for risk assessment. As future work, we intend to further exploit the multi-perspective risk representation capability of the TERMINUS ontology and study more deeply its impact on the overall risk assessment. This will be accomplished by providing the various types of experts with tailored functionalities aimed, for instance, at supporting the activity of forming risk assessment teams or at suggesting alternative risk perspectives.

ACKNOWLEDGMENTS

Authors acknowledge project RoMA (“Resilience enhancement of Metropolitan Area” PON MIUR SCN_00064), project RAFAEL (“System for Risk Analysis and Forecast for Critical Infrastructure in the ApenninEs dorsaL Regions” PON MIUR ARS01_00305) and project ARCH ("Advancing Resilience of Historic Areas against Climate-related and other Hazards“), funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 820999, for financial support. The sole responsibility for the content of this publication lies with the authors. It does not necessarily represent the opinion of the European Union. Neither the EASME nor the European Commission are responsible for any use that may be made of the information contained therein.

ORCID

Alex Coletti https://orcid.org/0000-0002-6263-1831
Antonio De Nicola https://orcid.org/0000-0002-1045-0510
Antonio Di Pietro https://orcid.org/0000-0003-4041-4913
Maurizio Pollino https://orcid.org/0000-0001-8244-303X
Vittorio Rosato https://orcid.org/0000-0003-4784-0069
Giordano Vicoli https://orcid.org/0000-0001-5048-1023
Maria Luisa Villani https://orcid.org/0000-0002-7582-806X

ENDNOTE

[1] Download link: https://www.unisdr.org/campaign/resilientcities/toolkit/article/quick-risk-estimation-qre

REFERENCES

Baldick, R., Chowdhury, B., Dobson, I., Dong, Z., Gou, B., Hawkins, D., … Zhang, X. (2008). *Initial review of methods for cascading failure analysis in electric power transmission systems IEEE PES CAMS task force on understanding, prediction, mitigation and restoration of cascading failures.* Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, IEEE.

Barcaroli, D., Coletti, A., De Nicola, A., Di Pietro, A., La Porta, L., Pollino, M., … Zavagnini, E. (2019). An automatic approach to qualitative risk assessment in metropolitan areas. *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2019)*, Valencia (Spain) 19th-22nd May, 2019.

Borst, W. N. (1997). *Construction of engineering ontologies for knowledge sharing and reuse*. Enschede, Netherlands: Centre for Telematics and Information Technology (CTIT).

Chesbrough, H. W. (2003). *Open innovation: The new imperative for creating and profiting from technology*. Boston, Mass: Harvard Business Press.

Coletti, A., De Nicola, A., Vicoli, G., & Villani, M. L. (2019). Semantic modeling of cascading risks in interoperable socio-technical systems. In K. Popplewell, K. D. Thoben, T. Knothe, & R. Poler (Eds.), *Enterprise interoperability VIII. Proceedings of the I-ESA conferences*, Vol. *9*. Cham, Switzerland: Springer.

Coletti, A., De Nicola, A., & Villani, M. L. (2016). Building climate change into risk assessments. *Natural Hazards*, *84*(2), 1307–1325. https://doi.org/10.1007/s11069-016-2487-6

Coletti, A., De Nicola, A., & Villani, M. L. (2017). Enhancing creativity in risk assessment of complex sociotechnical systems. In O. Gervasi, B. Murgante, S. Misra, G. Borruso, C. M. Torre, A. M. A. C. Rocha, … A. Cuzzocrea (Eds.), *Computational science and its applications – ICCSA 2017*. ICCSA 2017. Lecture Notes in Computer Science, Vol. *10405*. Cham, Switzerland: Springer.

Colton, S., & Wiggins, G. A. (2012). Computational creativity: The final frontier? In: *Proceedings of the 20th European conference on artificial intelligence*. IOS Press, pp. 21–26.

De Nicola, A., Melchiori, M., & Villani, M. L. (2019). Creative design of emergency management scenarios driven by semantics: An application to smart cities. *Information Systems*, *81*, 21–48. https://doi.org/10.1016/j.is.2018.10.005

Di Pietro, A., Lavalle, L. L., Porta, L., Pollino, M., Tofani, A., & Rosato, V. (2016). Design of DSS for supporting preparedness to and management of anomalous situations in complex scenarios. In R. Setola, V. Rosato, E. Kyriakides, & E. Rome (Eds.), *Managing the complexity of critical infrastructures: A modelling and simulation approach* (pp. 195–232). Cham, Switzerland: Springer International Publishing.

Dierich, A., Tzavella, K., Setiadi, N. J., Fekete, A., & Neisser, F. (2019). Enhanced crisis-preparation of critical infrastructures through a participatory qualitative-quantitative interdependency analysis approach. *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2019)*, Valencia (Spain) 19th-22nd May, 2019.

Elmhadhbi, L., Karray, M. H., & Archimède, B. (2019). A modular ontology for semantically enhanced interoperability in operational disaster response. *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2019)*, Valencia (Spain) May, 2019.

Erdik, M., Aydinoglu, N., Fahjan, Y., Sesetyan, K., Demircioglu, M., Siyahi, B., … Yuzugullu, O. (2003). Earthquake risk assessment for Istanbul metropolitan area. *Earthquake Engineering and Engineering Vibration*, *2*(1), 1–23. https://doi.org/10.1007/BF02857534

Gangemi, A., & Presutti, V. (2009). Ontology design patterns. In Staab S., Studer R., (Eds.), *Handbook on ontologies*, 2nd edn. *International handbooks on information systems*. Heidelberg, Germany: Springer.

Gaur, M., Shekarpour, S., Gyrard, A., & Sheth, A. (2018). empathi: An ontology for emergency managing and planning about hazard crisis. *arXiv*. preprint arXiv:1810.12510.

Giovinazzi, S., Pollino, M., Kongar, I., Rossetto, T., Caiaffa, E., Di Pietro, A., … Tofani, A. (2017). Towards a decision support tool for assessing, managing and mitigating seismic risk of electric power networks. In O. Gervasi, B. Murgante, S. Misra, G. Borruso, C. M. Torre, A. M. A. C. Rocha, … A. Cuzzocrea (Eds.), *Computational Science and Its Applications – ICCSA 2017*. ICCSA 2017. Lecture Notes in Computer Science, vol 10405. Springer, Cham.

Grafenauer, T., König, S., Rass, S., & Schauer, S. (2018). A simulation tool for cascading effects in interdependent critical infrastructures. In *Proceedings of the 13th International Conference on availability, reliability and security* (p. 30). ACM.

Greuel, C., Denker, G., & Myers, K. (2017). Semantic instrumentation of virtual environments for training. In *Proc. of MODSIM World 2017*. Virginia Beach, VA.

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge Acquisition*, *5*(2), 199–220. https://doi.org/10.1006/knac.1993.1008

Hayes, K., Blashki, G., Wiseman, J., Burke, S., & Reifels, L. (2018). Climate change and mental health: Risks, impacts and priority actions. *International Journal of Mental Health Systems*, *12*, 28. https://doi.org/10.1186/s13033-018-0210-6.

König, S., & Schauer, S. (2019). Cascading threats in critical infrastructures with control systems. *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2019)*, Valencia (Spain) 19th-22nd May, 2019.

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of Psychology*, *140*, 1–55.

Lückerath, D., Bogen, M., Rome, E., Sojeva, B., Ullrich, O., Worst, R., & Xie, J. (2018). The RESIN climate change adaptation project and its simple modeling approach for risk-oriented vulnerability assessment. In *Proceedings of ASIM-Workshop STS/GMMS* (pp. 21–26).

Matassoni, L., Giovinazzi, S., Pollino, M., Fiaschi, A. L., Porta, L., & Rosato, V. A. (2017). *Geospatial decision support tool for seismic risk management: Florence (Italy) case study*. ICCSA 2017. LNCS, Vol. 10405. Cham, Switzerland: Springer. 10.1007/978-3-319-62395-5_20

Mora, C., Spirandelli, D., Franklin, E. C., Lynham, J., Kantar, M. B., Miles, W., … Hunter, C. L. (2018). Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature*. *Climate Change*, *1*, 1062–1071. https://doi.org/10.1038/s41558-018-0315-6

Pahwa, S., Scoglio, C., & Scala, A. (2014). Abruptness of cascade failures in power grids. *Scientific Reports*, *4*, 3694.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, *21*(6), 11–25.

Sales, T. P., Baião, F., Guizzardi, G., Almeida, J. P. A., Guarino, N., & Mylopoulos, J. (2018). The common ontology of value and risk. In *International conference on conceptual modeling* (pp. 121–135). Cham, Switzerland: Springer.

Silva, V., Crowley, H., Pagani, M., Monelli, D., & Pinho, R. (2014). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards*, *72*(3), 1409–1427. https://doi.org/10.1007/s11069-013-0618-x

Taleb, N. N. (2010). *The Black Swan: The impact of the highly improbable fragility*. Random House LLC..

Taraglio, S., Chiesa, S. L., Porta, L., Pollino, M., Verdecchia, M., Tomassetti, B., … Lombardi, A. (2019). Decision support system for smart urban management: Resilience against natural phenomena and aerial environmental assessments. *International Journal of Sustainable Energy Planning and Management*, *24*, 135–146. https://doi.org/10.5278/ijsepm.3338

Teffali, S., Matta, N., & Chatelet, E. (2019). Managing stress with experience feedback in crisis situation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *33*(2), 206–225. https://doi.org/10.1017/S0890060419000106

Vicente, R., Parodi, S., Lagomarsino, S., Varum, H., & Silva, J. M. (2011). Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal. *Bulletin of Earthquake Engineering*, *9*(4), 1067–1096. https://doi.org/10.1007/s10518-010-9233-3

World Health Organization (2014). *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. Geneva, Switzerland : World Health Organization.

Zachos, K., Maiden, N., & Levis, S. (2015). Creativity support to improve health-and safety in manufacturing plants: Demonstrating everyday creativity. In *Proceedings of the 2015 ACM SIGCHI Conference* *on Creativity and Cognition*, C&C '15, ACM, New York, NY, USA, pp. 225–234.

Zanni-Merk, C., Cavallucci, D., & Rousselot, F. (2009). An ontological basis for computer aided innovation. *Computers in Industry*, *60*(8), 563–574. https://doi.org/10.1016/j.compind.2009.05.012

Zhu, X., Dai, Q., Han, D., Zhuo, L., Zhu, S., & Zhang, S. (2019). Modeling the high-resolution dynamic exposure to flooding in a city region. *Hydrology and Earth System Sciences*, *23*(8), 3353–3372. https://doi.org/10.5194/hess-23-3353-2019

How to cite this article: Coletti A, De Nicola A, Di Pietro A, et al. A comprehensive system for semantic spatiotemporal assessment of risk in urban areas. *J Contingencies and Crisis Management*. 2020;28:178–193. https://doi.org/10.1111/1468-5973.12309