An Automatic Approach to Qualitative Risk Assessment in Metropolitan Areas

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ABSTRACT

Risk assessment aims at improving prevention and preparedness phases of the crisis management lifecycle. Qualitative risk assessment of a system is important for risks identification and analysis by the various stakeholders and often requires multi-disciplinary knowledge. We present an automatic approach to qualitative risk assessment in metropolitan areas using semantic techniques. In particular, users are provided with a computational support to identify and prioritize by relevance risks of city services, through generation of semantic descriptions of risk situations. This approach is enabled by a software system consisting of: TERMINUS, a domain ontology representing city knowledge; WS-CREAM, a web service implementing risk identification and ranking functions; and CIPCast, a GIS-based Decision Support System with functions of risk forecast due to natural hazards. Finally we present the results of a preliminary validation of the generated risks concerning some points of interest in two different areas of the city of Rome.

Keywords

Risk assessment, geographic information system, conceptual modeling, ontology, computational creativity.

INTRODUCTION

Recent disasters in urban areas have caused an increasing interest in risk assessment. Knowing the possible risks for a specific area could increase the level of prevention and preparedness of a community to a crisis. Two types of approaches are commonly used for risk assessment of systems. Qualitative risk assessment involves system stakeholders to identify risk situations and prioritize them. Quantitative risk assessment, which may follow the qualitative approach, is performed by analysts to provide forecast of the impact of predefined risks, whenever the relevant event and system data are available. Examples of quantitative approaches include estimation of cascading failure propagation in electric power system (Baldick at al., 2008) and those devoted to compute the losses due to an earthquake (Silva et al. 2014). The qualitative approach for risk assessment is especially useful to identify possible new risks for an area, as the so-called *black swan* events. However current practices of qualitative risk assessment are heavily based on human judgment and experience, and this may weaken completeness and reliability of the results. Therefore, as a new research, we are facing the problem of how to automatize some human activities of qualitative risk assessment by exploiting Artificial Intelligence techniques.

In this context we propose an automatic approach to qualitative risk assessment in urban areas that aims at conceiving new risks for points of interest (POIs) in metropolitan areas and at prioritizing them. Examples of points of interests are hospitals, police stations, museums and restaurants. The approach is enabled by a software system that, in particular, generates conceptual models of risks, named risk mini-models (Coletti et al. 2017), and locates them on a map. The system consists of three main components: TERMINUS (Coletti et al. 2018), a domain ontology formalizing knowledge concerning environment, city services and infrastructures and related risks; WS-CREAM, a web service implementing the computational support for automatic risk identification and ranking, by querying the ontology and using context data; and CIPCast, a GIS-based tool for critical infrastructures protection, enhanced with forecasting and decision support functionalities.

The TERMINUS ontology was built by means of ontology design patterns. An ontology design pattern is a reusable conceptual structure with the aim of supporting the ontology engineering process (Gangemi and Presutti, 2009). WS-CREAM implements semantic queries automatically built from pre-specified ontology patterns[1].

Then we present the guidelines to perform qualitative risk assessment by means of the proposed software. The activities concern both the system set up and the actual qualitative risk assessment process.

As a case study we present the experience we had on qualitative risk assessment in the city of Rome. In particular, we focused on two areas with different characteristics. The former, the area close to Ponte Milvio, is located in the city center and close to the Tevere river. The latter, close to Colli Albani, is located nearby a lake and it is threatened by earthquakes. We discuss a preliminary experts' validation of the generated risk mini-models concerning the points of interest of these two areas.

The rest of the paper is organized as follows. The second section presents relevant work in the area. The third section describes the proposed software system for qualitative risk assessment. The fourth section presents the guidelines to perform qualitative risk assessment using the system. The fifth section describes the preliminary results of a case study of qualitative risk assessment in the city of Rome. Finally the last section presents conclusions.

RELATED WORK

This paper deals with risk assessment for metropolitan areas. As stated in Introduction the most common approaches for this purpose are quantitative and qualitative risk assessment. Among the existing works on quantitative risk assessment we cite: the seismic vulnerability and risk assessment performed by (Vicente et al., 2011) for the city of Coimbra in Portugal; the earthquake risk assessment for Istanbul metropolitan area treated by (Erdik et al., 2003); and the quantitative risk assessment performed by (World Health Organization, 2014) that, among the different causes of death, includes also costal flood mortality. Among the existing works concerning qualitative risk assessment we cite (Rinaldi et al. 2001) that discusses the risks due to interdependencies of critical infrastructures, With respect to these works our proposal addresses both approaches as CIPCast is mainly devoted to quantitative risk assessment whereas WS-CREAM, together with CIPCast, addresses qualitative risk assessment.

There are different initiatives in the literature devoted to building ontologies related to risk assessment. One of the first initiatives is the vulnerability upper model and the VUM ontology presented by (Coletti et al., 2016). The VUM ontology includes 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., 2018). After these, other initiatives include the common ontology of value and risk presented by (Sales T.P. et al. 2018) and the ontology of emergency managing and planning about hazard crisis presented by (Gaur, M. et al. 2018).

At the best of our knowledge, our is the first approach devoted to automatizing human activities of qualitative assessment and linking risk descriptions to system components on a map to the purpose of analysis.

[1] Similarly to an ontology design pattern, in the following, an ontology pattern is a reusable semantic model, based on the ontology that supports the definition of queries.

SOFTWARE SYSTEM FOR QUALITATIVE RISK ASSESSMENT

The automatic approach for qualitative risk assessment is realized within a wider system whose architecture is illustrated in Figure 1. Specifically, such a system realizes interoperation of two pre-existing applications, such as an ontology-based CREAtivity Machine Web Service (WS-CREAM) and CIPCast, a GIS-based Decision Support System (DSS) for critical infrastructures protection with a web interface. A middle layer, such as the Semantic data Integrator, was realized to manage communication between the two independent back-end components. In summary, for a user selection of an urban area and of a natural hazard from the WebGIS interface (i.e. CIPCast front-end), TERMINUS ontology, representing city knowledge, together with context data managed by CIPCast geodatabase, are used by WS-CREAM to generate ranked lists of risk descriptions for the services belonging to that areas. These risks, after off-line validation, are shown on the map as result.

A more detailed description of the system components follows.

The CIPCast Decision Support System

CIPCast is a novel Decision Support System (DSS) (Giovinazzi et al., 2017) able to produce a real-time operational risk forecast of CI in a given area due to natural hazards. The main functionalities of CIPCast are: (i) real-time monitoring of natural phenomena; (ii) prediction of natural events (if predictable); (iii) prediction of damage scenario on critical infrastructure components; (iv) prediction of impacts on critical infrastructure services and impacts on citizens and (v) definition of efficient strategies to support decision-making operator processes.

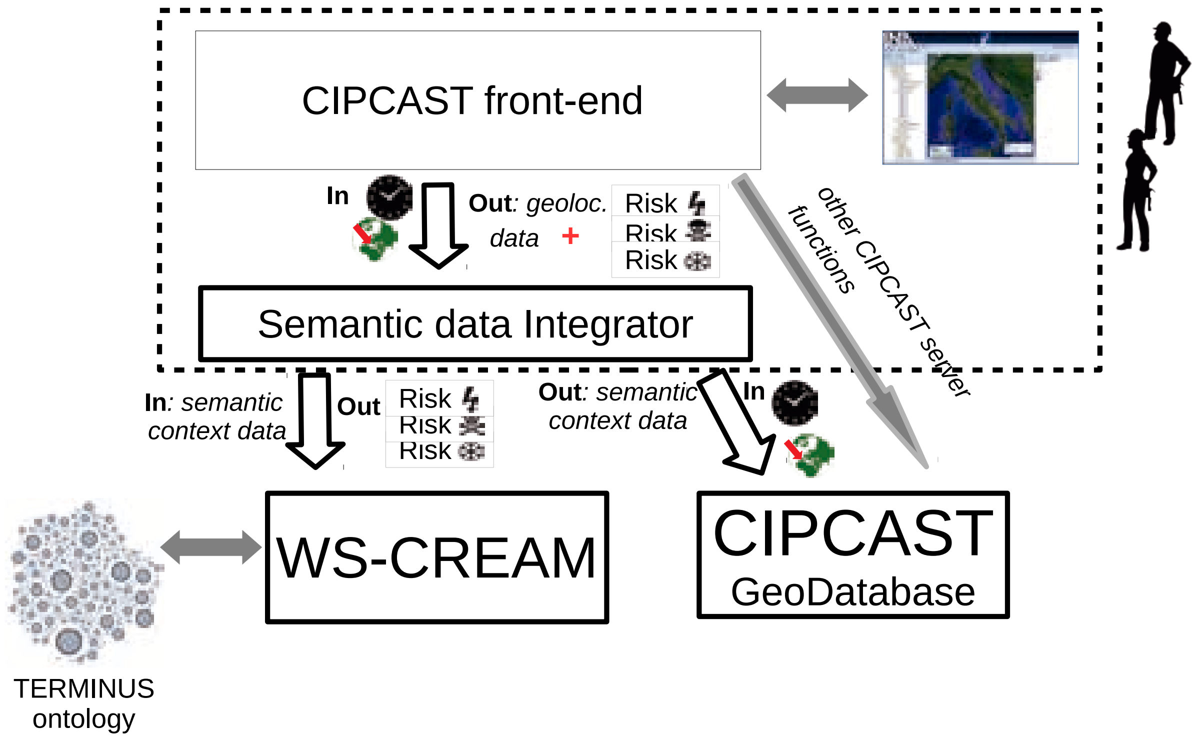

Figure 1 Illustration of the software architecture and information flow

CIPCast was conceived as a combination of free/open source software (FOSS) environments including Geographic Information System, GIS features, which play a major role in the construction of such a tool. Multisource data and GIS-integrated analysis can contribute to a better emergency planning, providing fundamental information for immediate response. The creation of this information consultation tool, enriched by the geospatial component, implies the adoption of a specific and suitable GIS architecture (commonly indicated as SDI, Spatial Data Infrastructures). In order to store and share all data and information available (base cartography, risk maps, CI features data, data from sensors, scenario produced, etc.), a PostGIS[2]-based

[2] https://postgis.net/

Geodatabase for data storage and management was implemented. The Geodatabase can be directly accessed by means of different desktop GIS software suites (e.g., QGIS). In addition, by means of the server stratum, composed by GeoServer[3], data can be accessed via web by using OGC standards[4] (WMS, WFS and WCS services).

Moreover, CIPCast provides a user-friendly geographical interface, implemented through a specific WebGIS application[5], for querying and analysing geographic data and thematic maps, execute processes and simulations, produce and evaluate scenarios, etc. Thanks to the WebGIS interface, the main results produced within CIPCast can be easily accessible to the users and exploitable for further analyses.

An Ontology for Territorial Management and Infrastructures

TERMINUS (TERritorial Management and INfrastructures ontology for institutional and industrial USage) is a domain ontology including knowledge representing 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 built 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., 2018) and from the *risk of system service* design pattern that is presented in the following. It 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 2. It consists of five upper level concepts: `Hazard`, `Critical_event_of_system`, `Functional_vulnerability`, `System_service`, and `Stakeholder`. The descriptions of these five upper level concepts is presented in Table 1 whereas the descriptions of the relationships between them is presented in Table 2.

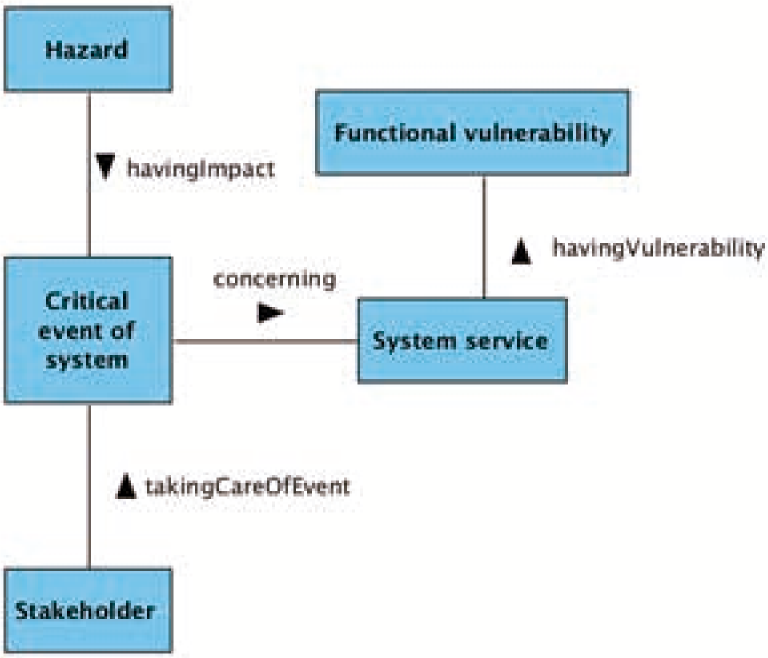

Figure 2. UML class diagram of the risk of system service ontology design pattern

[3] http://geoserver.org/

[4] Open Geospatial Consortium standards: http://www.opengeospatial.org/docs/is

[5] Developed exploiting the GeoPlatform FOSS suite: https://github.com/geosdi/geo-platform

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

Concept name	Description
`Hazard`	Climate-related event or trend or their impacts on geophysical systems (e.g., floods, droughts and sea level rise) with likely detrimental consequences to human systems (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 description in 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 concept description in 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 the 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`.

Figure 3 shows an excerpt from TERMINUS ontology showing a fragment of the taxonomy related to the `System_service` concept.

WS-CREAM

The CREAtivity Machine (CREAM) Web Service is a software application that, more generally, is capable to automatically generate semantic descriptions of future situations that may be significant in some given application domain to the purpose of analysis. These situations refer, for example, to possible emergencies in a city or to risks for infrastructures or enterprises. The aim is to support a user, such as a risk analyst or a city planner, to imagine possible futures and identify those relevant for her final objectives, including city emergency management and/or risks mitigation. Indeed, this component provides an automatic ranking of the generated situations, based on context information, a useful function to speed up the subsequent qualitative assessment activity by the user, .

From a technical perspective, WS-CREAM has been realized to be independent from the specific application (risk assessment or emergency scenarios planning), hence to be adaptable to different uses by means of some configuration information.

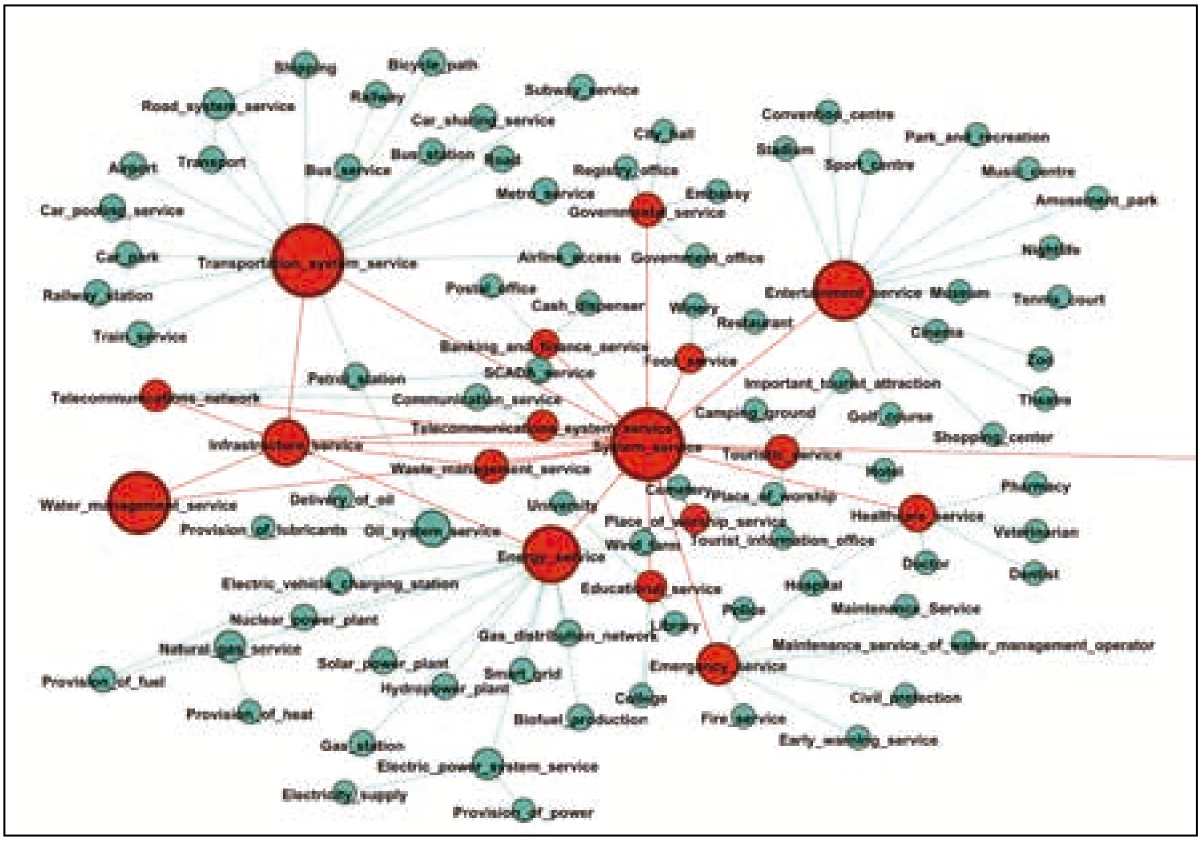

Figure 3. Excerpt from TERMINUS ontology showing a fragment of the taxonomy related to the `System_service` concept

In this work, WS-CREAM uses the following input configuration specifying:

- the **application domain**, here represented by the TERMINUS ontology;
- the **semantic structure** (by means of a formal ontology pattern) of the information on the situation to be represented. Here such a structure is described in OWL and it is based on the ontology design pattern described previously. The output risks will be described as records of the following table.

  [*System service, Hazard, Functional vulnerability, Critical event of system, Stakeholder*] (1)
- a **ranking formula** to be applied to order by relevance level the generated risks for each city service. Such a formula is defined by the metrics: context-specific properties of the service, such as its relevance as point of interest in the given city, its physical exposure to risks caused by the given hazard; and context-independent properties of the service, such as the service criticality compared to other services of a city (e.g., hospital versus monument). The formula also specifies the aggregation operations of those variables.

For the application presented in this paper, as a trial, the ranking formula is the *average* of the relevance levels attributed to some components of the ontology design pattern, that is: the *relevance* of the specific service in the city, such as its *value* or *criticality* in the city, associated with the *System service* component in (1); the *risk level* from a natural hazard, referred to the geographical location of the service, associated with the *Hazard* component of (1); the *criticality level* of the described impact of the natural event on the service, compared to other types of impact, associated with the *Critical event of system* component of (1); the *relevance level* of the functional vulnerability, compared to other known vulnerabilities, associated with *Functional vulnerability*.

Given such a configuration, WS-CREAM provides a function that takes as input a list of semantically annotated services present in a user selected urban area, their contextual properties; and possibly the type of hazard with its associated properties. A SPARQL query (Coletti et al., 2017) is automatically built from a pre-defined ontology pattern addressed in the configuration file, which is run on the TERMINUS ontology to retrieve a list of semantic descriptions of possible service risks as records of (1). These records are built with concepts of TERMINUS, where the *System service* component specifies the type of service provided as input, and, possibly, the *Hazard* component specifies the type of chosen hazard. For each city service, WS-CREAM computes a relevance level of each generated risk (in a ordinal scale from 1 to 5), using the ranking formula. The output will be a set of associations of the city services with their ranked lists of risks.

GUIDELINES FOR QUALITATIVE RISK ASSESSMENT

In our proposal qualitative risk assessment requires six activities. The first three activities are related to the system set up, whereas the last three concern the actual qualitative risk assessment process.

1. **Points Of Interest (POI) identification.** This set up activity consists in identifying points of interest located in the area considered for the analysis, like restaurants, hospitals, cinemas and governmental offices.
2. **Semantic annotation of the POIs**. This set up activity consists in providing a formal meaning to the points of interest identified in step 1. So each point of interest is associated with a formal expression. For instance, POI:`Stadio_Olimpico IS_INSTANCE_OF TERMINUS:Stadium` specifies that *Stadio Olimpico* of Rome is annotated by the `TERMINUS:Stadium` ontology concept.
3. **Definition of the ranking mechanism**. This set up activity consists in deciding the ranking formula and collection of the required data to prioritize the generated risks.
4. **Risk mini-model generation for a selected area**. This activity consists in using the system to generate ranked risk descriptions, named risk mini-models (RMM), for the POIs of the selected area.
5. **Risk mini-model validation**. This activity involves experts to assess RMM usefulness and relevance.
6. **Geolocalization of risk mini-models**. This activity consists in using the system to visualize the valid risk mini-models on a map.

CASE STUDY: QUALITITATIVE RISK ASSESSMENT IN ROME (ITALY)

This case study is related to qualitative risk assessment concerning two areas of Lazio (Italy): the area near Ponte Milvio, in the center of Rome and close to the Tevere river, and Colli Albani, an area on the hills in the south-east of Rome. For these areas we identified the points-of-interests.

Ponte Milvio

Considering the morphology of this area and its proximity to Tevere river, our study focused on the alluvial event that, historically, has frequently occurred in this area. The points-of-interests located in this area are all located inside buildings and mainly include medical offices, dental offices, restaurants and are homogeneously located throughout the territory. Some of such points-of-interests are particularly relevant due to their high occupancy rate. These include the Olympic stadium, the Auditorium Parco della Musica, the Palazzetto dello Sport and the IUSM University of Rome. Regarding the presence of points-of-interests not included into buildings, these include petrol stations and tennis courts.

Colli Albani

This area, including a portion of territory between the lakes of Albano and Nemi, has suffered damages following seismic events in history. The points-of-interests are all located inside buildings and, mainly, include restaurants, medical offices, veterinary offices, dental clinic, museums, hotels and libraries.

In the following we present a risk mini-model for the Ponte Milvio area and another one for the area of Colli Albani. These were selected by experts as representatives of the most relevant risk mini-models. Each risk mini-model is followed by a description written by the expert, in the form of an imagined story or report of a known situation. The purpose is to provide context-based interpretation of the risk mini-model and to support risk plausibility. This method follows the approach to stimulate creativity presented by (De Nicola et al., 2019).

Ponte Milvio risk mini model
`Functional_vulnerability: People_inside`
`System_service: Nightlife`
`Critical_event_of_system: Health_and_physical_consequences`
`Stakeholder: Unspecified_person`
`Hazard: Flood`

Description
A flood occurred in the center of Rome; it hits a very popular nightclub of the area while this was registering its maximum capacity of customers. The water caused physical damages and also health consequences to people inside the nightclub. Indeed, the panic of the mass generated fights to exit the structure resulting in several injured persons.

Colli Albani risk mini-model

`Functional_vulnerability: Presence_of_electric_elements_potentially_dangerous`
`System_service: Doctor`
`Critical_event_of_system: Economic_damage`
`Stakeholder: Manager`
`Hazard: Earthquake`

Description
It is 9:00 am on a weekday. The waiting room of a medical office is, as usual, full of: patients waiting for their turn; secretaries; doctors and staff involved in their work. At 9:15 a strong earthquake causes breakage of machinery and electrical tools that begin to fall dangerously over the patients; moreover, the general panic in the waiting room grows as the large neon lights come off the supports, creating some injuries. A few minutes later the medical office is evacuated, but the general chaos produces considerable damage to electrical equipment and specialist instruments, computers and printers, the general electrical panel, lights, etc. These damages have an economic impact on the medical service .

In the following we present the analysis of the results after the experts' validation of the risk mini-models generated by WS-CREAM. Table 3 shows the number of relevant risk mini-models with respect to the overall set. It shows that, for the two considered areas, the percentages of relevant risk mini-models are 37.77% and 53.88%. As a future work, discarded risk mini-models will be used to learn rules to improve precision of the generative function of WS-CREAM.

Table 3. Number of relevant generated risk mini-models according to the expert's judgment. This analysis considers the type of system service.

Area	**Relevant risk mini-models**	**Overall risk mini-models**	**Percentage of relevant risk mini-models**
Ponte Milvio	431	1141	37.77%
Colli Albani	534	991	53.88 %

Table 4 shows the degree of relevance of generated risk mini-models according to the expert's judgment. It should be noted that the numbers of risk mini-models are higher with respect to those presented in Table 3 as here these numbers include POI instances. This means that there could be more than one medical office in the selected area.

Table 4. Degree of relevance of generated risk mini-models (by POI) according to the expert's judgment. This analysis considers the different POIs (there could be more POIs for one type of system service).

Area	**Number of relevant risk mini-models**	**High relevance**	**Medium relevance**	**Low relevance**
Ponte Milvio	827	124 (14.99%)	431 (52.12%)	272 (32.89%)
Colli Albani	809	343 (42.39%)	162 (20.02%)	304 (37.58%)

Table 5 shows the degree of relevance of generated risk mini-models according to WS-CREAM ranking.

Table 5. Degree of relevance of generated risk mini-models (by POI) according to WS-CREAM ranking. This analysis considers the different POIs (there could be more POIs for one type of system service).

Area	Number of relevant risk mini-models	High relevance	Medium relevance	Low relevance
Ponte Milvio	2122	1180 (55.61%)	942 (44.39%)	0 (0%)
Colli Albani	1472	0 (0%)	1320 (89.67%)	152 (10.33%)

Then we compared the relevance level assigned by the experts to risk mini-models with that assigned automatically by WS-CREAM. We found that the expert and the software judgments were the same for 210 out of 809 risk mini-models (25.96%) in case of the area of Colli Albani and for 373 out of 827 risk mini-models (45.10%) in case of the area of Ponte Milvio. Again we expect to improve these numbers in the near future, for instance, by gathering more accurate context-specific and context-independent data and experiencing different ranking formulas. Finally Figure 4 shows a screenshot of CIPCast including the risk mini-models generated by WS-CREAM for the point of interest doctor in case of flooding.

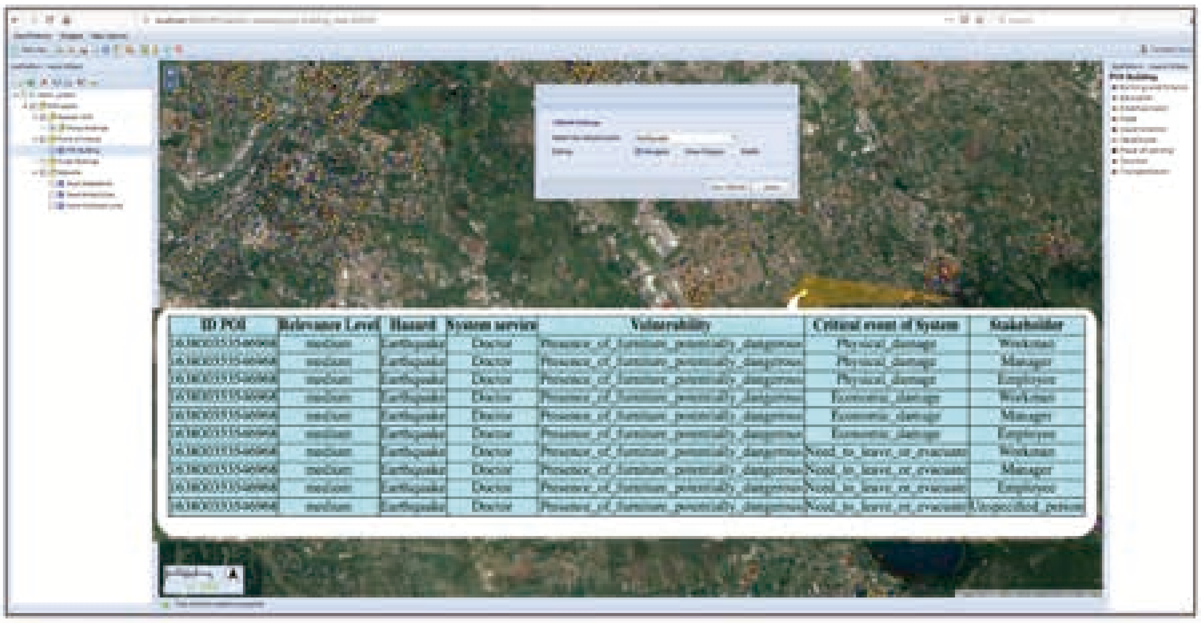

Figure 4. Risk mini-models associated to points of interest located in the area of Colli Albani (Rome) in case of flooding.

CONCLUSION

Qualitative risks assessment for metropolitan areas is a complex activity due to uncertainties on hazards and to the variety of systems. WS-CREAM is a novel software system aiming to provide descriptions of relevant risk situations with semantic reasoning applied to a domain ontology. As risk assessment requires data on the geographical areas and on the societal and infrastructures' characteristics of the specific system under analysis, WS-CREAM has been integrated with CIPCast, which is a GIS-based tool for CI protection, enhanced with forecasting and decision support functionalities. In this work, we presented how these two systems interoperate to perform qualitative risk assessment for metropolitan areas. We presented also preliminary validation results of the approach. These results provided us future work directions to improving selectivity of the risk mini-models generation function and precision of the automatic assessment.

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