DISCOVERY OF HIDDEN VULNERABILITIES IN CRITICAL INFRASTRUCTURES

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Alex Coletti[1], SMRC, Sterling, VA,
Antonio De Nicola, M. L. Villani, and G. Vicoli, ENEA, Roma, Italy

1. INTRODUCTION

Infrastructures, such as transportation, telecommunication, water distribution and energy services, are prime examples of sociotechnical systems. They are complex and becoming increasingly interconnected at the point that failures of one can propagate to others with possible consequences on community's livelihood and prosperity (Rickert, et al. 2011, Weijnen, et al. ,2008).

The analysis of likely cascading mishaps is essential for planning preventive risk measures. however, since failure rates can change with time, societal resilience, systems design and re-allocation of resources, frequent reviews and flexible management practices need to be applied.

In this context, system actors, such as managers and operators, need access to tools that enable them to share information with other work-groups with similar interests but different experiences. For example, the present need of critical services to inform users on their functional status could offer a vehicle suitable for facilitating such sharing of information (Figure1).

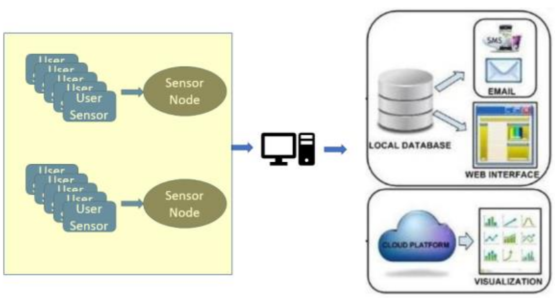

Figure 1: Conceptual diagram of a utility sensor network collecting data on usage, distributing information to users, and storing information on data cloud.

We propose to augment the risks elicitation process of managers and operators participating in focus groups through a suite of semantics-based tools implementing computational creativity techniques. Our solution consists of applying a set of rules to a domain ontology based on the Vulnerability Upper Model (VUM, Coletti et al., 2016) originally developed for Community Water Systems. A computational creativity software system, Creativity Machine (CREAM), uses the rules to generate plausible risk scenarios from a set of real-life risk models De Nicola et al. (2014a), Milly et al (2008).

This paper first describes the risks identified by experts during real-life focus group sessions that we used to build our VUM ontology model. The next section describes the conceptual templates that were extracted from the observed risks and that are at the core of the CREAM software system functionality. Lastly, this paper outlines how the CREAM software system can be a useful virtual apprentice that assists human experts in risk assessments processes while also learning from their decisions.

2. VULNERABILITY UPPER MODEL

Since the development of the NOAA Community Vulnerability Assessment Tool (Watson, 2009), several attempts were made to apply information technologies to qualitative and quantitative vulnerability assessments. While most vulnerability assessments provide information on current and past local events, they have limited ability in including cumulative risk effects of interconnected infrastructures and smart systems (Abbott, 2009, De Nicola et al., 2014b, Shahanas, 2016).

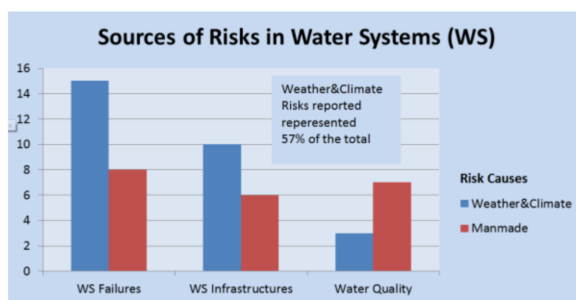

Figure 2: Number of Water System (WS) risk types identified by experts during the focus group experiments. The focus groups identified 15 types of WS risks due to weather and climate and 10 risks WS experience as they percolate from interconnected infrastructures.

As an example, Figure 2 shows the results of an experiment conducted on focus groups of

[1] *Corresponding author address:* Alex Coletti, SMRC, 20145 Boxwood Pl, Ashburn, VA 20147, USA. E-mail: coletti@smrcusa.com

experts of Community Water Systems. In the experiment, almost 90% of all risk types were attributed directly or indirectly to natural hazards affecting interconnected infrastructures (Coletti et al., 2012).
These findings hint to the possibility that:

1. quantitative information on hazards, vulnerabilities, and losses can be reliably quantified from focus groups;
2. actively coordinated focus group activities can provide clear and transferable descriptions of risk stories in natural language.

Follow-up work on the data set in Figure 2 managed to compare quantitative risk estimates with equivalent qualitative focus group results by linking design elements, vulnerabilities, and hazards within a single ontology model.
The analysis led to the definition of a more general and essential set of risk concepts that were collected in a Vulnerability Upper Model (VUM). This new system-type independent ontology consists of concepts linked to each other by a somewhat lower number of properties (Coletti et al. 2012). Interestingly, the organization of the VUM succeeded in organizing all the elements in the vulnerability assessment into proper hierarchical lists. Figure 3 shows a pictorial representation of the core VUM.
While the semantic framework based on the VUM succeeds in organizing descriptions of all the risks identified by the stakeholders of the experiment into an ontology, it also provided the methodology for knowledge enrichment. In principle, information already accessible on-line can be mined and structured according to the VUM based methods to substantiate relationships between different and new risk elements. These machine generated risks models can both be used to verify the correctness and the completeness of the VUM ontology, and to identify new, logically possible, risk situations.
To test the feasibility of this option, we designed and built a CREAM software system for the generation of creative risk insights from sets of mini-models.

3. A RISK MODEL GENERATOR FOR CREAM

Risk mini-models have the construct of conceptual templates such as for example: system risk, system, hazard, threat, severity, vulnerability and stakeholder (Figure 4) (Coletti et al. 2017; De Nicola et al. 2014a). Each mini-model identifies threats and vulnerabilities of a given risk from the stakeholders' perspective. A risk model instead consists of a set of risk mini-models that fully describes a specific risk type. Risk mini-models, once stored into a knowledge base, enrich a socio-technical system risk model that can be useful in the analysis of similar types of systems.
Since mini-models are only templates of concepts, they facilitate the sharing of ideas in focus groups because they do not include information on any particular system.

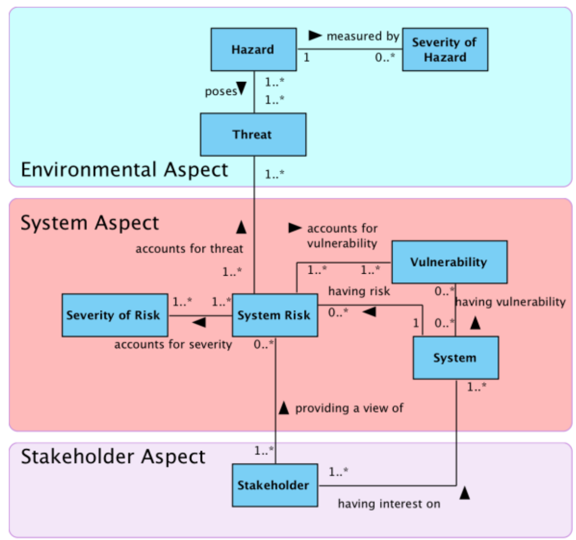

Figure 3: The diagram of the Core VUM

The machine selects the topics while guiding the decision process protocol for the focus group coordinator. This way, the machine guides the creative spark, overcomes the geographical differences and minimizes the effects of the personality barriers that often constrain brainstorming discussions. This overall process is represented in Figure 5 (Coletti et al. 2017].

SYSTEM	HAZARD	THREAT
SEVERITY	VULNERABILITY	STAKEHOLDER
SYSTEM RISK		

Figure 4: Risk mini-model template

Since the machine also keeps track of the many-to-many failure relationships of the

interconnected systems (Milly et al. 2008), focus group can leverage the multidisciplinary knowledge experts provide by leaving the machine to deal with the internal complexities of the system.
Our computational creativity approach models the risk identification process as a search process within a space consisting of the VUM based ontology. The ontology is constrained by its own contextual rules while it is dynamically updated and refined by the system during each iteration of the process.

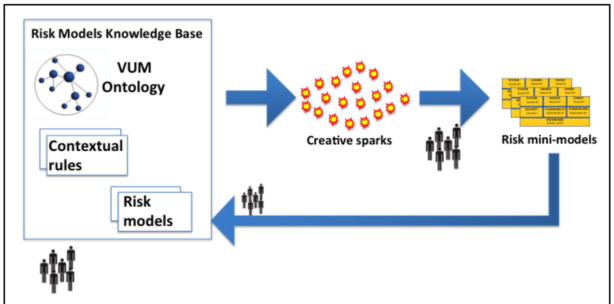

Figure 5: CREAM-based system for risk assessment consisting of the Ontology Management System (OMS), the rules editor, the CREAM, the validation tool, and the risk models' knowledge base

The three informational sources used by the CREAM are the risk mini-model, the system domain, and the query context form. The contextual rules of the semantic bindings in the SPARQL queries are selected by the focus group (Perez et al. 2006). Therefore, a VUM pattern-based query is formed by a set of risk mini-models that are the result of:

- linking each sematic relationship pattern to one of the object properties
- associating each VUM construct in the relationship to a leaf subclass of the VUM concept.

This pattern-based query can be refined with contextual rules, each providing a filter SPARQL statement. Presently, CREAM is implemented in Java and is based on the Apache Jena framework that includes the ARQ library Apache (2013), and supports a SPARQL 1.1 engine. The application is configurable with respect to the ontology, contextual rules and query patterns (risk mini-models) by means of a XML file.

4. CONCLUSIONS

Risk assessment of complex sociotechnical system requires both a deep knowledge of the infrastructure and a creative attitude in envisioning system mishaps. Furthermore, since failure rates change with time, societal resilience, systems design and re-allocation of resources, frequent reviews and flexible management practices are increasingly needed. The CREAM software system addresses these issues by acquiring the needed system knowledge from an ontology. In turn, our approach hypothesizes the presence of sets of users whose activities, discussions and validation of the machine-generated suggestions also improve the system performance.
CREAM leverages two of its primary functionalities to improve system's performance. Firstly, the sharing of experiences among geographically distributed and socio-economically separated focus groups facilitates the semantic binding of the risk mini-models. Secondly, the machine generated creative spark, while driving the discussion toward added creativity and original thinking, also cuts across properties of critical infrastructures, personality barriers, and the biases that often affect focus group deliberative objectivity.

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