Towards a Common Ontology for Investigating Resilience of Interdependent Urban Systems

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Summary

In the presented work, we aim to investigate the overall resilience of the interdependent critical infrastructures (CI) energy, water and information and communication technology (ICT). Due to its multidisciplinary character, a joint resilience evaluation of interdependent CI networks such as water and electricity is a challenging task. The presented work proposes to approach this challenge by developing a common ontology within which the interoperability between the heterogenous domains (CI networks, resilience evaluation, disruption events) is ensured by the means of an upper-ontological level. Moreover, a novel methodology of classifying disruption events is proposed, distinguishing disruption events based on their temporal and spatial scope. This abstract and generalised classification will allow us to assess the resilience regardless of the specific cause of an event. It is argued that a common ontology will improve resilience evaluation by preventing organisational errors, information redundancies and inconsistencies.

Keywords

Resilience; Critical Infrastructure; Ontology; Water-Energy-Nexus; Interdependence

Introduction

Current trends in urban development point towards the establishment of Smart Cities. This term reflects increasing permeation of the urban sphere with information and communication technology (ICT) [1, 2]. While the digitalised control of the already inter-linked urban water and energy supply networks with the communication networks is beneficial in numerous ways, it also increases the interdependence between the critical infrastructures (CI) which gives rise to new vulnerabilities.

Problem Statement

The presented work is part of the LOEWE-Project emergenCITY, in which we aim to study jointly rather than separately the resilience of various urban CI networks such as energy, water and ICT. This will allow for an improved overall evaluation, since interdependence of different types of CI can be responsible for increased vulnerability as a disruption affecting one network may ripple across to others in case of strong coupling [3]. Modelling, development, operation and maintenance of the different networks rest in the hands of different strands of the engineering domains while representatives of other disciplines such as sociology, history and law consider the behaviour of their users. These groups need to collaborate to study the effect of disruptions on infrastructure of digital cities and their communities [4]. Due to the strong heterogeneity of these groups, it is essential to agree on a common language with regard to disruption events when developing a strategy to improve the resilience of urban CI.

Consequently, we propose to develop a common ontology for the water and energy networks within which these events can be expressed and which makes it possible to interpret those events with regard to their effect on the interdependent networks. This will allow us to assess their combined resilience.

Terminology

In the following section, the understanding of the terms CI, resilience and ontology is clarified, as these are the most central to our work.

The European Union defines CI in legislation as: “An asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people.” [5] By contrast, the definition of the United States stresses the aspect of collaboration between individual infrastructures which is a precondition for the successful delivery of essential goods and services, since none of the CI networks individually fulfil all of the functions referred to in the EU definition, and none of the functions are fulfilled in total by one specific CI [6].

The concept of resilience has been defined in various ways by different organisations and authors [7–9]. A meaningful interpretation of this concept for the domain of engineering which considers the interpretations of resilience in various other disciplines is given by Altherr et al.: “A resilient technical system guarantees a predetermined minimum of functional performance even in the event of disturbances or failure of system components, and a subsequent possibility of recovering at least the setpoint function.” [10] They further identify four resilience core functions, namely monitoring, responding, learning and anticipating.

Finally, it is necessary to clarify what is understood by the term ontology in the context of this work. Originating in philosophy, ontology is also used in computer engineering where Gruber defines it as “an explicit specification of a conceptualization.” [11] The following interpretation of this definition is given by H. Sack: conceptualization denotes the abstract model of the most relevant concepts and relations in a domain of interest. It is explicit in that the meaning of each of the components must be defined. The multiple stakeholders in the ontology must have the same understanding of the concepts and their definitions. Furthermore, for beneficial use in computer engineering it should be formalised so as to be machine understandable. [12]

Relevant Work

Several ontologies have been proposed in the context of emergency response [13–17]. Kontopoulos et al. developed an ontology for climate crisis management [18]. Further works also consider CI interdependencies [19–21]. Specializing on federated simulation frameworks for investigating the dependencies between critical infrastructures, Tofani et al. developed a knowledge base system based on ontological formalism [22]. However, most of these works are concerned with ontologies intended for emergency or crisis management and situation assessment, not resilience analysis. As such, they mainly serve to describe the situation and assist humans in the decision process rather than to perform engineering analyses and evaluate resilience metrics. While they often manage to include social aspects, an in-depth ontology capable of capturing the cyber-physical nature of infrastructures with a simultaneous possibility of resilience assessment has not been proposed so far.

Developing an Ontology

In order to design an ontology capable of providing a stable basis for resilience analysis of interdependent CI systems, the fundamental methodology of Uschold and Gruninger [23] and the methodology for catastrophe situation assessment of Little and Rogova [15] are used. According to Uschold and Gruninger, developing a formal ontology should start by identifying the motivating scenarios. In the present case, the motivation lies in the need to assure interoperability between three key aspects: the interdependent CI networks, the disruption events and the resilience metrics. Following [23], we specify a set of competency questions (natural language sentences the ontology should be able to answer), such as “What is the minimum required water/energy supply of a specific city district?” and “Which components of the CI are still functioning during a disruptive event?”.

The description of disruptive events and their effect on CI is not a trivial task. We define disruptive events in that we identify potential causes of disruptions. Abstracting from specific causes, we categorise disruptive events along generalised criteria common to all realistic disruptive events. These are the temporal and spatial scope of a disruptive event (instantaneous/persistent, local/global), as shown in Figure 1. E.g., an event that causes a disruption of just one component in the water network but several components distributed throughout the studied domain in the energy network is classified as global, since the scope in both networks is observed in analysing the disruption event. Similarly, components failing in both networks at the same geographic location are interpreted as a local disruptive event. The temporal scope of the disruptive event is determined by the time frame within which the first and the last disruption occurs. Rather than planning the robustness of the CI against a set of specific pre-defined events, this simple yet comprehensive classification will allow us to assess the resilience of the CI faced with any given disruptive event.

This categorisation is a first step towards deriving an ontology for the domain of disruptive events. Further ontology domains will be developed for the CI networks and the resilience metrics based on the existing ontologies, lexical sources, scientific literature and domain experts. While the domain-specific ontologies provide concrete content necessary to understand a situation, an upper-level ontology can improve the analysis of numerous domain-specific items by informing about the domain's metaphysical structure [15]. As a result, we identify the need for an upper-level ontology (ULO) which is able to integrate the domain-specific ontologies of individual CI networks, resilience evaluation and disruption events. We propose to find a suitable ULO upon consideration of the existing models (e.g., [20, 22]). The main challenge will lie in expressing interdependencies and linking the events with the CI networks.

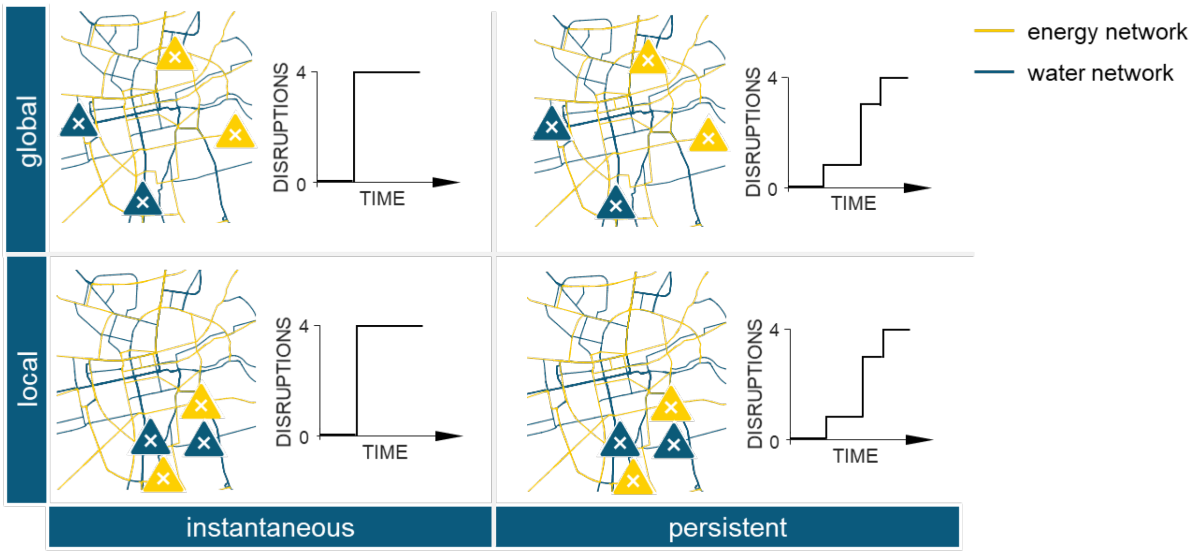

Figure 1: Classification of disruption events.

Conclusion

We identify a common ontology as an appropriate approach to assess the combined resilience of interdependent CI. Aside from describing CI networks, the ontology will be designed to account for the effect of various disruption events on a generalised level. The basic categorisation proposed here can easily be expanded to include concepts as intensity and temporal evolution of a disruption as well as a continuous scope rather than discreet categories, in case this proves more advantageous. In future work, we will show that a common ontology can in addition improve the overall resilience of interdependent CI by avoiding information redundancies and enabling a coordinated response from all networks.

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