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# Evaluation of the robustness of critical infrastructures by Hierarchical Graph representation, clustering and Monte Carlo simulation

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ABSTRACT

In this paper, we present a methodological work that adopts a system-of-systems (SoS) viewpoint for the evaluation of the robustness of interdependent critical infrastructures (CIs). We propose a Hierarchical Graph representation, where the product flow is dispatched to the demand nodes in consideration of different priorities. We use a multi-state model to describe different degrees of degradation of the individual components, where the transitions between the different states of degradation occur stochastically. The quantitative evaluation of the CIs robustness is performed by Monte Carlo simulation. The methodological approach proposed is illustrated by way of two case studies: the first one concerns small-sized gas and electricity networks and a supervisory control and data acquisition (SCADA) system; the second one considers a moderately large power distribution network, adapted from the IEEE 123 node test feeders. The large size of the second case study requires hierarchical clustering for performing the robustness analysis.

## 1. Introduction

Critical infrastructures (CIs) are complex systems essential for providing goods (e.g., energy) and services (e.g., transportation) across local, regional and national boundaries [1]. Typically, they present both structural and dynamic complexities. The former derive from i) heterogeneity of components across different technological domains, due to the integration among different systems and ii) scale and dimensionality of connectivity through a large number of components (nodes), highly interconnected by dependences (unidirectional relationships) and interdependences (bidirectional relationships). Dynamic complexity manifests through the emergence of (unexpected) system behavior in response to changes in the environmental and operational conditions of its components. Furthermore uncertainties exist in the failure behavior of CI components, interconnections and interactions, so that the prediction of CI failure behavior is difficult [2].

*Engineered, physically networked* CIs are considered in this paper. Examples are those providing: energy (electricity, oil and gas supply as subsectors); transportation (by rail, road, air, shipping); information and telecommunication (such as the internet); drinking water, including wastewater treatment, etc.

Due to the increasing complexity of CIs, random failures, natural events and malevolent attacks can have severe consequences on health, safety, security, economics and social well-being. In this respect, evaluating the robustness of CIs is fundamental to be able to improve their design and management so to reduce the impacts of disruptive events. There is no unique definition of robustness. Jensen defines it as the degree to which a system can function correctly in the presence of inputs different from those assumed [3]; for Carlson and Doyle [4], and Jen [5], the robustness guarantees the maintenance of certain desired system characteristics, despite fluctuations in the behavior of its components or in its environment. Jen [5] and Ali et al. [6] specify that the concept of robustness should be defined for a given set of system features, under a given set of perturbations applied to the system. According to Foster, robustness is the ability of a system to react to noisy input parameters with little performance degradation [7]. A recent definition of robustness is given in the glossary of the specialty group on “Foundations of Risk Analysis” of the Society for Risk Analysis, as the antonym of vulnerability [8]. In addition, a system is considered robust to uncertainty if specified goals are achieved, despite large information gaps (information gap is the disparity between what is known, and what needs to be known to ensure specified goals) [8]. In this work, robustness is seen as the capability of the CIs to resist to failures or partial failures of the CIs components assuring the required level (or a high level) of supply of goods or services.

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Traditionally, three steps are performed in the robustness assessment of CIs: (i) the system is represented to define the structural, logical and functional relations among its components; (ii) a mathematical model of the system is built to quantify its performance indicators; (iii) the model is solved, e.g., by simulating its behavior under different operational and accidental conditions.

With respect to system representation (i), several types of approaches exist in literature, many of which rely on a hierarchy or graph structure. Hierarchical modeling has been often adopted to represent and model complex systems, since many organizational and technology-based systems are hierarchical in nature [9,10]. Hierarchical functional models include Goal Tree Success Tree (GTST) [11] – also combined with Master Logic Diagram (MLD) [12] – and Multilevel Flow Models (MFM) [13,14]. In risk analysis, common representation techniques are hierarchical trees that are possibly used to identify i) the initiating causes of a pre-specified, undesired event or ii) the accident sequences that can generate from a single initiating event through the development of structured logic trees (i.e., fault and event trees, respectively) [15]. Recently, also networks have been represented by hierarchical modeling [16,17].

In complex network theory approaches, instead, complex systems are represented by networks where the nodes stand for the components and the links describe the physical and relational connections among them [18–22]. Network-based approaches model interdependent CIs on the basis of their topologies or flow patterns [23]. Physical and non-physical (heterogeneous) overlapping infrastructures have been represented as networks to identify risk scenarios and the impacts on connected networks in [24]. Also probabilistic methods (e.g., Petri nets [25], Bayesian networks [26] and flowgraphs [27] are based on graph representations.

In this paper, we present a methodological work that embraces a system-of-systems (SoS) framework of analysis [28,29,1,30] and propose a Hierarchical Graph representation to evaluate the robustness of interdependent CIs, measured by its capability to deliver the required amount of product (e.g., energy, water, etc.) to the demand nodes of the infrastructure. In this respect, the system can be considered robust if it can maintain the required level (or a high level) of delivery when it is affected by perturbations (failures and partial failures). In doing so, we take into account the fact that the demand nodes may have different importances, which leads to possibly different priorities in the distribution of the product flow through the connections to the elements of the CI. For example, hospitals may be considered more important than residential buildings given their role in the health-care system; as a consequence, in the case of a reduction of electric power that can be delivered in the network, hospitals may receive the priority with respect to houses. This ranking of priority should be fixed by the analyst and, then, criteria (hereafter also referred to as "importance criteria") for the partition of the flow (e.g., electric power) in the network can be defined. In this work, we assume three different importance criteria that depend on the geographic position of the demand nodes, the quantity of product required by each of them and the assumption of equality of the demand nodes.

The representation proposed consists of a graph structured in hierarchical levels that allows highlighting critical arcs and supporting the quantitative robustness evaluation by assigning different priorities to the demand nodes. Critical arcs are here defined as those links whose interruption or degradation affects several demand nodes. This concept of criticality can be related to that of "importance measure" used in reliability theory. Actually, importance measures quantify the contribution of a given component to a properly selected measure of system performance (e.g., robustness in this case): see, for example, the Birnbaum [31], Fussell and Vesely [32] criticality importance measures [33], etc. More specifically, with respect to network system analysis, other importance measures have been defined to measure component criticality ([1,34]), like classical topological centrality measures including the degree of centrality [35,36], the closeness centrality [36,37,38], the betweeness centrality [36] and the information centrality [39].

For a more realistic representation, we adopt a multi-state model where different degrees of degradation of the individual components are contemplated [40,41]; the transitions between the different states of degradation occur stochastically and are modeled within Markov and semi-Markov processes.

For illustration purposes, we consider two case studies: the first one is characterized by small-sized interconnected gas and electricity networks and a supervisory control and data acquisition (SCADA) system [42]; the second one is adapted from the IEEE 123 node test feeders [43] and includes a large electricity distribution network. The first case study is chosen small enough to be able to clearly illustrate the Hierarchical Graph modeling of (three) connected systems, considering different priorities of the demand nodes. The second case study serves the purpose of showing how the approach can be extended when the size of the system increases.

As a measure of the robustness of the system, we evaluate the steady-state probability distributions of the product (e.g., gas and/or electricity) delivered to the demand nodes.

The quantitative evaluation of the system robustness is performed by Monte Carlo (MC) simulation [44,45]; in the second case study of larger dimension, an unsupervised spectral clustering algorithm is employed to make the size of the CI manageable and reduce the computational burden related to the analysis [46].

The remainder of the paper is organized as follows. In Section 2, the Hierarchical Graph representation is introduced and the importance criteria considered are illustrated; in Section 3, the procedural steps to evaluate the robustness of interconnected CIs by Hierarchical Graph and MC simulation are provided, and the combination of Hierarchical Graph and clustering analysis is given, then the advantages and limitations of the approach are discussed; Section 4 contains the description of the two case studies, the representation of the corresponding systems and the results obtained; in Section 5, some conclusions are provided. Finally, in Appendix A the data related to the second case study are illustrated.

## 2. Hierarchical Graph representation of systems of systems

The proposed representation technique can be applied to *engineered, physically networked* CIs (energy, transportation, information and telecommunication) characterized by a radial structure, i.e., by unidirectional flows of "products" (power, water, gas, data). Actually, the representation requires that the CI of interest be first modeled by a directed graph of nodes and arcs without loops (in this case, the arcs may represent elements of an infrastructure or the connections between different infrastructures). Typical radial systems are the distribution networks.

To build the Hierarchical Graph representation, we then need to distinguish between input, demand (load) and transmission arcs: the "input arcs" connect the production sources to the network, the "demand arcs" terminate with nodes that require a given amount of product, whereas the "transmission arcs" transfer the product to other components in the network. Notice that the transmission and the demand arcs may coincide: for example, an arc may be needed to supply the connected node and in addition it may be required to transmit the product to other arcs/nodes.

In the Hierarchical Graph representation, the adjective "hierarchical" does not imply a "decomposition of the system into different levels of details", as in other hierarchical models (e.g., Goal Tree Success Tree – Dynamic Master Logic Diagram [12] and