Extension of DMCI to heterogeneous infrastructures: model and pilot application

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Abstract: Since the adequate functioning of critical infrastructures is crucially sustaining societal and economic development, the understanding and assessment of their vulnerability and interdependency become more and more important for improving resilience at system level. The paper proposes an extension of DMCI (Dynamic Functional Modelling of vulnerability and interoperability of CIs) to modelling the vulnerability and interdependencies of heterogeneous infrastructures, i.e. the interactions between electric power infrastructure and the transport infrastructure system have been modelled. The simulation tool has been implemented with the Matlab platform Simulink in order to overcome some computational limitations, that affect the first DMCI version implemented in Matlab, in quantifying the propagation of inoperability and logical interdependencies related to demand shift, and to obtain a modular and user friendly solution, even for users who are not expert at simulation.

The new DMCI model has been tested with a pilot application that comprised more than 200 vulnerable nodes and covered both power transmission grid and transportation systems of the province of Milan (Italy). The most vital and vulnerable nodes have been identified under different blackout scenarios, for which specific data on vulnerable nodes has been collected directly from the operators.

Keywords: CIP, interdependencies, simulation, electricity, transportation.

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1. INTRODUCTION

Critical Infrastructures are those assets, systems or parts thereof, which is essential in the provision of services that are deemed to be vital for the functioning of society, ‘‘including the supply chain, health, safety, security and economic or social well-being of the people’’ [1]. Since the adequate functioning of those infrastructures is crucially sustaining societal and economic development, the understanding and assessment of their vulnerability and interdependency become more and more important for improving resilience at system level.

CIs are highly interconnected and mutually interdependent [2] [3]. On the one hand, interdependencies have allowed a greater availability of resources but, on the other hand, they have increased their vulnerability; indeed, even a relatively small malfunctioning of an infrastructure can have considerably large and long-lasting effects on the whole infrastructural network due to largely unpredictable domino effects [4]. Recent worldwide events such as the 2001 World Trade Center Attack, the 2003 Italian and North America blackouts, the 2005 hurricane Katrina, the 2008 UK floods, and the 2011 Japan earthquake have sensibly influenced both the public opinion and the governments all around the world, enhancing the interest in how those destruction or disruption events propagate within the network of Critical Infrastructure.

Existing simulation approaches to vulnerability and interdependency analysis of complex CIs networks refer to different scientific fields, e.g. physical network modelling, network economics, etc. [5]. In the last decade, many approaches to CI protection have been developed. In this regard, Ouyang [6] provides a comprehensive review on modeling and simulation of interdependent critical infrastructure systems and groups the modeling approaches into six types: empirical approaches, agent based approaches, system dynamics based approaches, economic theory based approaches, network based approaches, and other approaches.

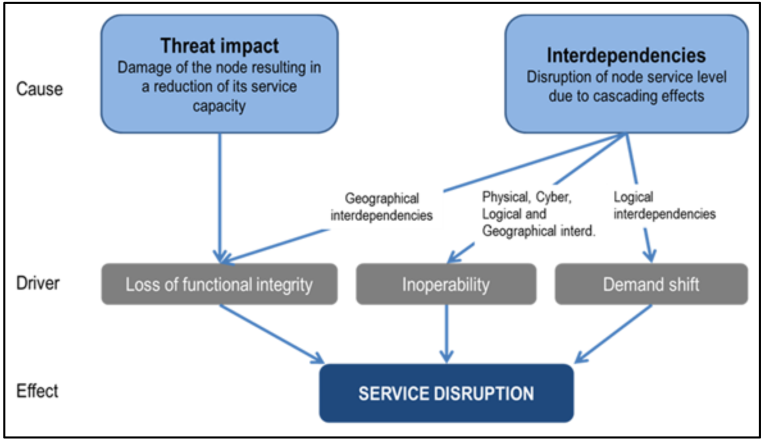
The present paper proposes an extension of the Dynamic functional Modelling of vulnerability and interoperability of CI (DMCI) formalism [7] to the problem of heterogeneous infrastructure modeling, e.g. the interdependencies between electric power infrastructure and the transport infrastructure systems. The paper is organized as follows: Section 2 summarizes the approach and key features of the first DMCI model; Section 3 describes the new modularized and enhanced implementation of DMCI formalism, with a special focus on how it can be applied to heterogeneous infrastructure systems; Section 4 presents the pilot application in the area of the province of Milan (Italy); Section 5 draws general conclusions on achieved results, major limitations and suggestions for further research.

2. FUNCTIONAL DYNAMIC MODELLING OF CRITICAL INFRASTRUCTURE

Trucco et al. in 2012 [7] developed a new integrated formalism for the Dynamic functional Modelling of vulnerability and interoperability of CI (DMCI). The proposed modelling formalism is characterised by some distinctive features:

- specification of vulnerable nodes defined as "*a large functional part of a CI that assures the satisfaction of a considerable part of service demand at regional or local level (e.g. part of a pipeline network, a railway station, a portion of a highway, an underground line) and that does not need further disaggregation for the sake of the analysis.*" A vulnerable node has to be homogeneous (i.e. uniform in structure and function with respect to service demand), service self-providing (i.e. a system able to supply a value-added service through own means), and vulnerable (i.e. susceptible to threats that could decrease its functional integrity). Vulnerable nodes are mutually connected to create intra- and inter-infrastructure interdependencies;
- specification of threat nodes, characterised by time-variant intensity and specific potential impact on different vulnerable nodes;
- quantification of both functional and logic interdependencies thanks to the use of both service demand and service capacity for each node of the considered CI;
- time dependent specification of the main parameters of the model: node functional integrity, interoperability, service demand and loss, etc.;
- propagation of both inoperability and demand variations throughout the nodes of the same infrastructure and between interdependent CI.

Figure 1: Causes of service disruption



The model, firstly implemented in a software code by Matlab®, is able to assess the propagation of impacts due to a wide set of threats. Therefore, the disservice can be propagated within the same infrastructure or to other CI exploiting the model capability to represent functional, cybernetic, geographical, physical as well as logical interdependencies.

Service level can be reduced either by a threat impact on node or through interdependencies (Figure 1). Functional integrity quantifies the direct impact of threats on the node service capability, i.e. the reduction of its maximum service capacity over time (the direct effect). Inoperability quantifies how disturbances coming from the CIs network through interdependencies (physical, cyber, geographical, logical – [8]) reduce the maximum service level of a node starting from its actual service capacity. As a consequence, service disruption, globally, is due to combined effects of loss of functional integrity on some nodes and propagation of inoperability between nodes.

In order to test the capability of the model to represent all the types of interdependencies and to give an overview of the possible outcome of the model a pilot study has been carried out in the metropolitan area of the province of Milan (Italy) in which the considered CI referred to the transportation system (road, rail, underground, and airport systems) [7]. In particular, for the road system, it has been considered highways, beltways and the national roads.

Afterwards, Cagno et al. [9] applied DMCI to analyze a real scenario – the ex-post analysis of the overall impact on the transportation system of the severe snowfall that took place in the Northern part of Italy in December 2009.

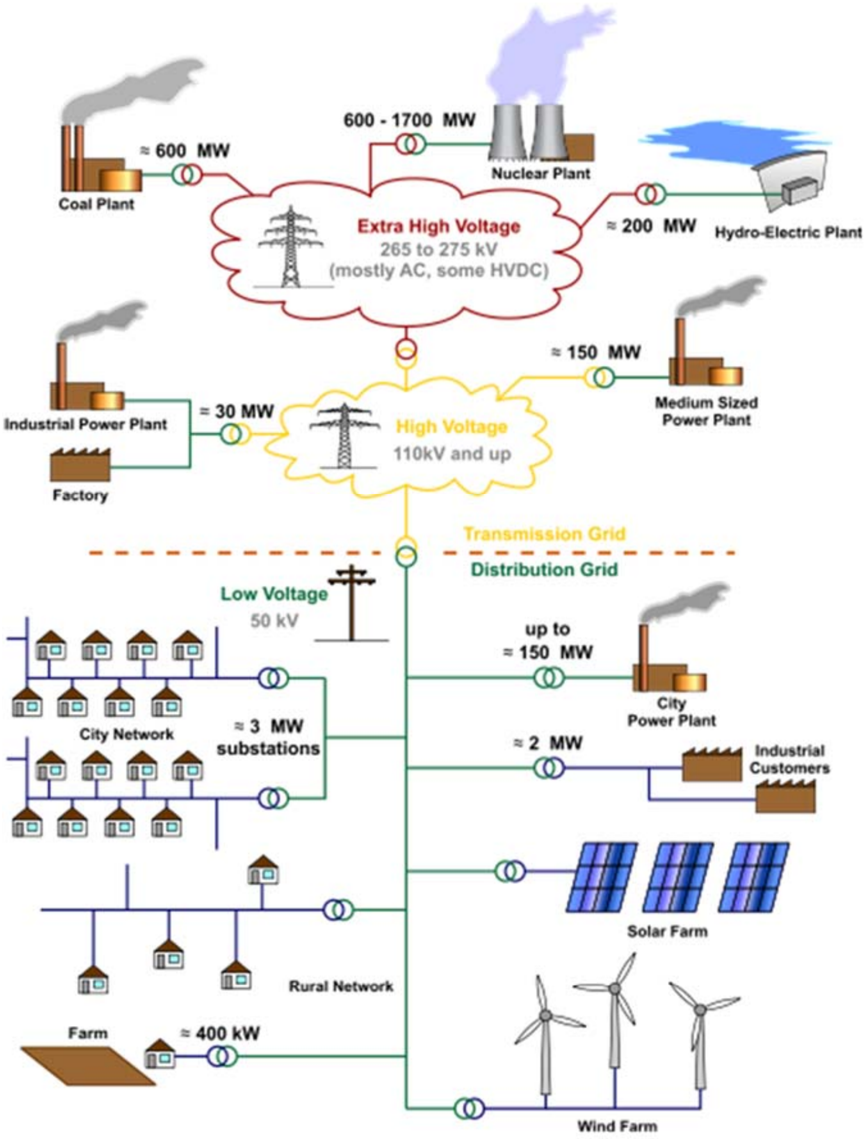
3. THE EXTENDED DMCI TO HETEROGENEOUS CRITICAL INFRASTRUCTURE

To fully test and eventually prove the potentials of DMCI its application to the case of heterogeneous interdependent CI is crucial. Indeed, more complex, unpredictable and as such potentially impacting domino effects are those due to interdependencies (more specifically inoperability propagation) among infrastructure of different nature. On this regard, an important stream in literature is the study of cyber interdependencies between Electricity and ICT infrastructure through SCADA systems [10] [11] [12] [13] [14] [15] [16]. Similarly relevant, but relatively less studied is the coupling of Transportation and Electricity infrastructure. As a matter of example, logical interdependencies are particularly relevant in both infrastructure systems. In the former, logical interdependencies are mainly established by the shift of demand between two infrastructure that can provide the same or fully/partially replaceable mobility service (e.g. two different transportation means to connect the same towns); in the latter, they are established by the way different power generation sources or line sections are used to maintain the overall grid balance.

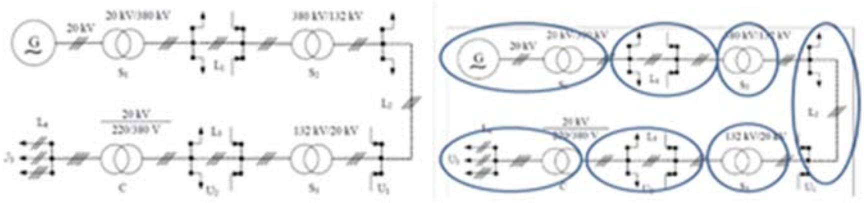
ortation infrastructure systems.

Figure 2 shows how the Electricity infrastructure, from power generation to distribution, can be functionally modeled into vulnerable nodes under the DMCI formalism. Whereas Figure 3 highlights key functional (a) and logical (b) interdependencies between vulnerable nodes of the Electricity and Transportation infrastructure systems.

Figure 2: Functional modeling of electricity infrastructure

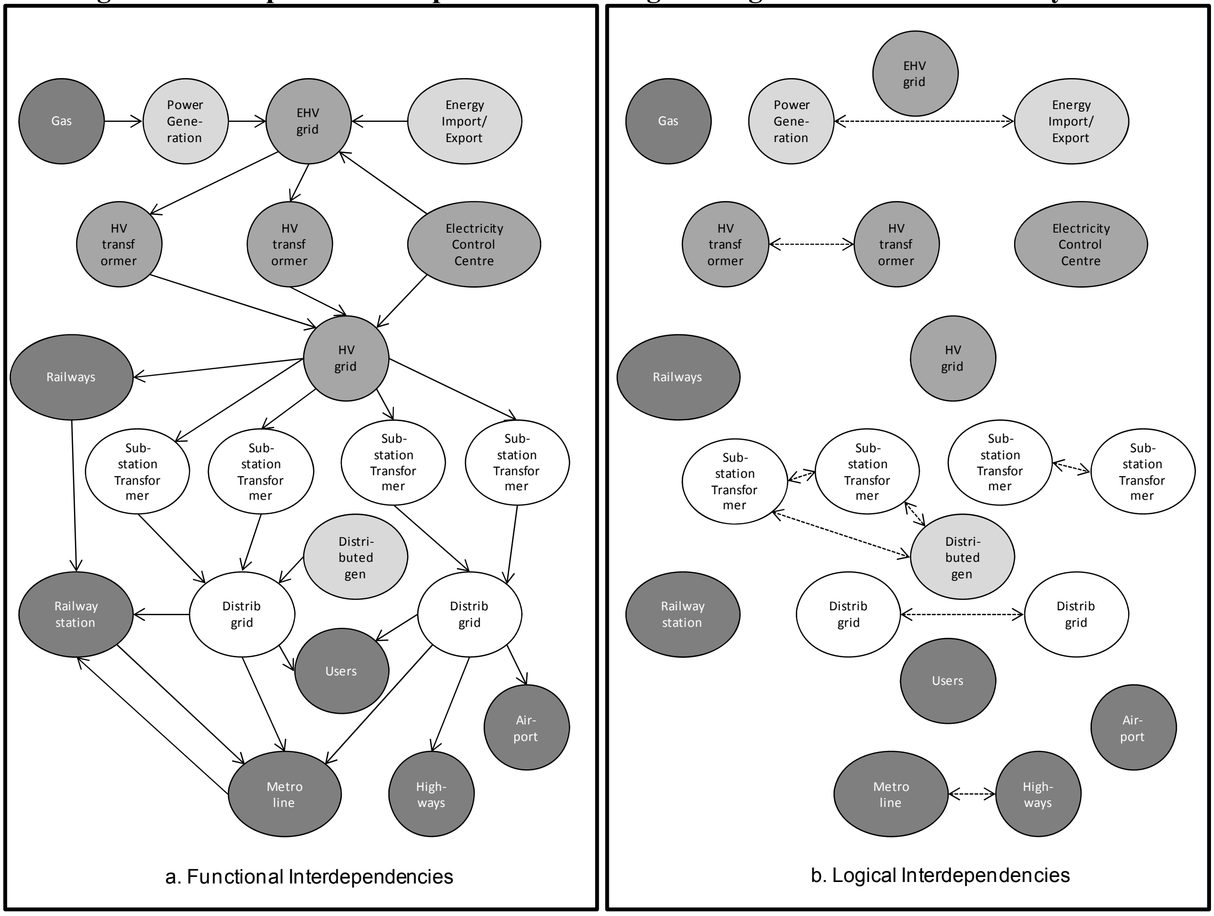


a. General layout of electricity grid



b. Diagram of electricity grid c. Nodes of electricity grid (in DMCI)

Figure 3: Example of interdependencies among heterogeneous infrastructure systems



3.1. DMCI Modularization

In order to overcome some computational limitations, that affect the first DMCI version implemented in Matlab®, mainly in quantifying the propagation of inoperability and logical interdependencies related to demand shift and to obtain a modular and user friendly solution, even for users who are not expert at simulation, such as policy makers or risk manager, the simulation tool has been implemented with the Matlab platform Simulink®.

Simulink® is a block diagram environment for multidomain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB®, enabling you to incorporate MATLAB® algorithms into models and export simulation results to MATLAB® for further analysis. The key aspect of modularization is the definition of a standard vulnerable node, whether if it is a transportation node or an electricity node.

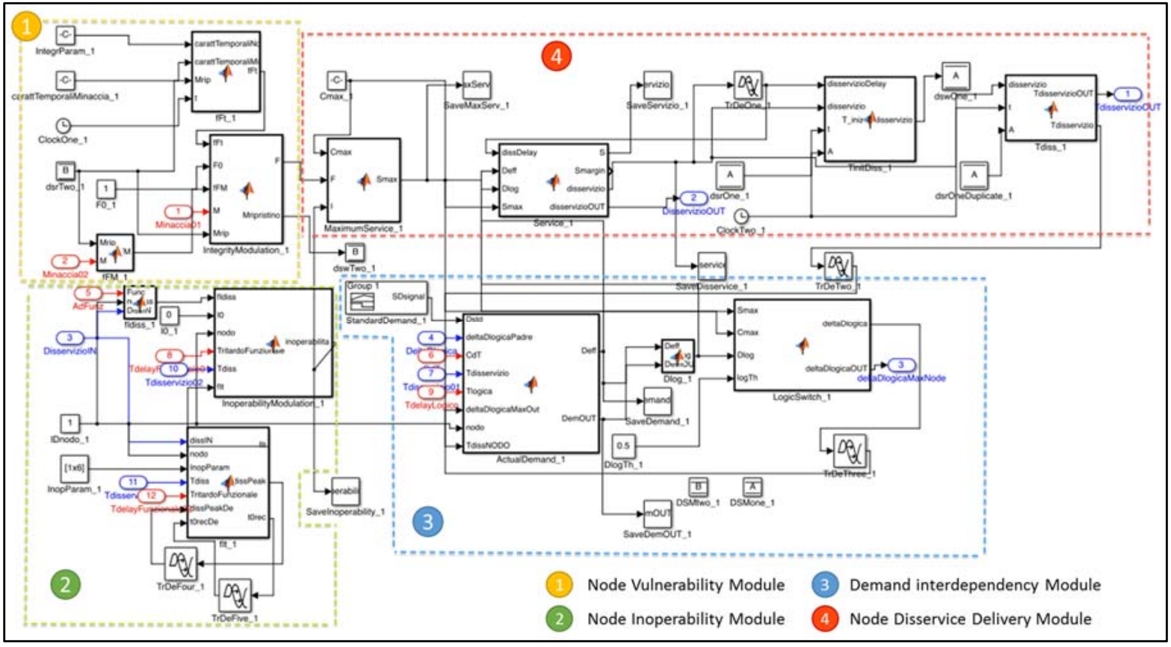
The standard vulnerable node developed in Simulink® (Figure 4) is built up of 4 principal modules: node vulnerable module, node inoperability module, demand interdependency module, node disservice delivery module.

Exploiting the capabilities of Simulink®, the simulator automatically builds up the network topology of vulnerable nodes and quantifies major model parameters starting from a simple user interface.

3.2. Node Vulnerability module

The Node Vulnerability module assesses the potential damage of a vulnerable node impacted by a threat. According to the first DMCI model, the threat impacting at time t on the k-th vulnerable node, causes a reduction of its functional integrity $F(k,t)$. The reduction depends on the functional integrity modulation function that defines the functional integrity steady reduction after the impact and the temporal modulation function that defines the dynamic through which the functional integrity reaches its new steady value [7]. The cause-effect relationship between threats and vulnerable node is modeled by means of three Simulink blocks: one is responsible for the temporal modulation of the threat, another for the intensity modulation and a third combining both modulations and calculates the functional integrity.

Figure 4: Vulnerable node developed in Simulink®



From a mathematical point of view, the threats are temporary signals with values between 0 and 1.
The main variables and parameters considered of the module are:

- Functional Integrity *F(k,t)* – quantifies how the threats directly impacting on the k-th node reduce its maximum service level $S_{max}(k,t)$ at time *t* (the direct effect), and it is comprised between 0 (the k-th node is completely blocked) and 1(optimal state);
- Parameters of *F(k,t)* – is a vector of four components that defines the dynamic response of the node to the threat. The four components are:
    - Buffer Time: time elapsed since the node is impacted until it begins to suffer any effect;
    - Propagation Time – is the duration of the first transient over which the *F(k,t)* reached the functional integrity steady reduction after the impact of the threat;
    - Organizational Time – is a minimum time required for setting-up a countermeasure after an integrity loss due to the threat. Thus, it is the time elapsed since the node is impacted until it begins to recovery its functional integrity;
    - Recovery Time – is the duration of the transient over which the node recovers its full functional integrity;

The profile of the transients are exponential functions.

3.3. Node Inoperability Module

The node inoperability module assesses the inoperability of the node due to physical and cybernetic interdependencies. The physical and cybernetic interdependencies operate when the father node transfer a disservice to the child exploiting a supplier-customer relationship. The inoperability of the node depends on the intensity modulation function $fI_{diss}(\mathrm{j},\mathrm{i})$ that defines the inoperability steady reduction of the j-th child node due to the disservice of the i-th father node and the temporal modulation function fI_t that defines the profile curve of the transient regime through which the j-th child node reaches its inoperability steady value as well as recovers from it.

The intensity modulation function fI_{diss} depends on the disservice of the father node calculated in the previous iteration and on the parameter $F_{prox}(i,j)$, of the functional interdependency matrix $F_{prox}(NxN)$, that indicates the sensibility of the j-th child node to the disservice of the i-th father node in terms of maximum reduction of its service capacity.

The temporal modulation function is composed by five phases:

- Functional buffer period: is the first phase runs from the father node begins to indicate disservice until the child node begins to suffer the effects in terms of inoperability; it is indicated into the T_{func} matrix;
- Inoperability propagation: period in which the inoperability of the node is growing. We assume that the profile is a typical feature of the node response;
- Higher steady state: in this phase the time modulation function is 1 until the recovery transient starts;
- Recovery transient: period in which the node recovers its service capacity lost due to functional relationships. The recovery starts when the disservice of the father node is less than the percentage of its maximum value defined by the parameter *recovery threshold*. The parameter $diss_{peak}$ is used to store for each iteration the maximum value of the disservice of nodes. The duration of the recovery is described by the parameter *recovery time* t_{rec}.
- Lower steady state: during this last phase the value of the temporal modulation function is 0. The duration of this phase is not predefined, but can be followed by a new functional buffer period that results in a new inoperability cycle.
- The transient periods (inoperability propagation and recovery) allows four types of profile: linear, step function of constant value between 0 and 1, negative exponential function, or positive exponential function.

The inoperability of the j-th node is calculated through the following equation:

$$I(j) = \begin{cases} 0, & \sum_j fI_t(i,j) * fI_{diss}(i,j) < 0 \\ \sum_i fI_t(i,j) * fI_{diss}(i,j), & 0 < \sum_j fI_t(i,j) * fI_{diss}(i,j) \leq 1 \\ 1, & \sum_j fI_t(i,j) * fI_{diss}(i,j) > 1 \end{cases} \tag{1}$$

3.4. Demand Interdependency Module

The demand interdependency module assesses the logical interdependencies and computes the actual demand of each node. The module is composed by three computational steps:

- actual demand $D_{act}(i,t)$ – depends on the standard demand $D_{std}(i,t)$ of the node, the total incoming demand $D_{IN}(i,t)$ and the total demand out $D_{OUT}(i,t)$. The $D_{IN}(i,t)$ is the demand incoming from other nodes j that provide the same service or fully/partially replaceable service but they are not able to completely satisfy at time *t* their actual demand and therefore send a percentage $CdT(j,i)$ of their unsatisfied demand in the previous iteration $\Delta D_{log}(j,t-1)$. In the same way, $D_{OUT}(i,t)$ is the $CdT(i,j)$ part of the demand the i-th node is not able to satisfied at time t that is sent to the j-th nodes;
- logical demand $D_{log}(i,t)$ – is the maximum amount of demand that the i-th node can send to others at time t;
- $\Delta D_{log}(i)$ – is defined as the difference between the logical demand $D_{log}(i,t)$ and the maximum service $S_{max}(i)$.

All the demand shift mechanisms can be triggered after a logical buffer time $T_{log}(i,j)$ that is the time after which the demand of the i-th father node begins to switch to the j-th child node (e.g. the time after which the railway users decide to switch to the road transportation system).

3.5. Node Disservice Delivery Module

The node disservice delivery module aims at computing all the variables related to the service level of the node. The module is setup of three blocks: the maximum service block, the actual service block, and disservice time block.

The entire computational process followed by the simulator at each iteration to determine the overall state of a node is:

- calculation of functional integrity F through the node vulnerability module;
- calculation of inoperability I through the node inoperability module;
- execution of the maximum service block to determine S_{max};
- calculation of the variables actual demand D_{act}, total incoming demand D_{IN}, and total demand out D_{OUT} through the demand interdependency module;
- calculation of the disservice $diss$, the marginal service S_{margin} that is the percentage of the S_{max} which is not currently used, and the disservice time $T_{diss}(i,t)$ through the execution of the actual service block, and disservice time block of the node disservice delivery module.

4. PILOT APPLICATION

4.1. Case description and simulation settings

In order to demonstrate the potential of the new DMCI, this section shows its application to the heterogeneous CI system that takes place in Milan, Italy. For this pilot application, the same system as described in [9] has been used. The system consists of over 200 nodes which describe several critical infrastructures of both the transportation and energy distribution networks. The first include road, railway and suburban transportation networks. The airports of Malpensa and Linate are also considered. The latter mainly covers the electricity distribution grid and some parts of the gas distribution network. Figure 5 shows the approximate layout of the electric grid nodes in the system and highlights the most important nodes involved in the scenario simulated in this pilot application.

Figure 5: Electrical grid nodes considered in the pilot application.

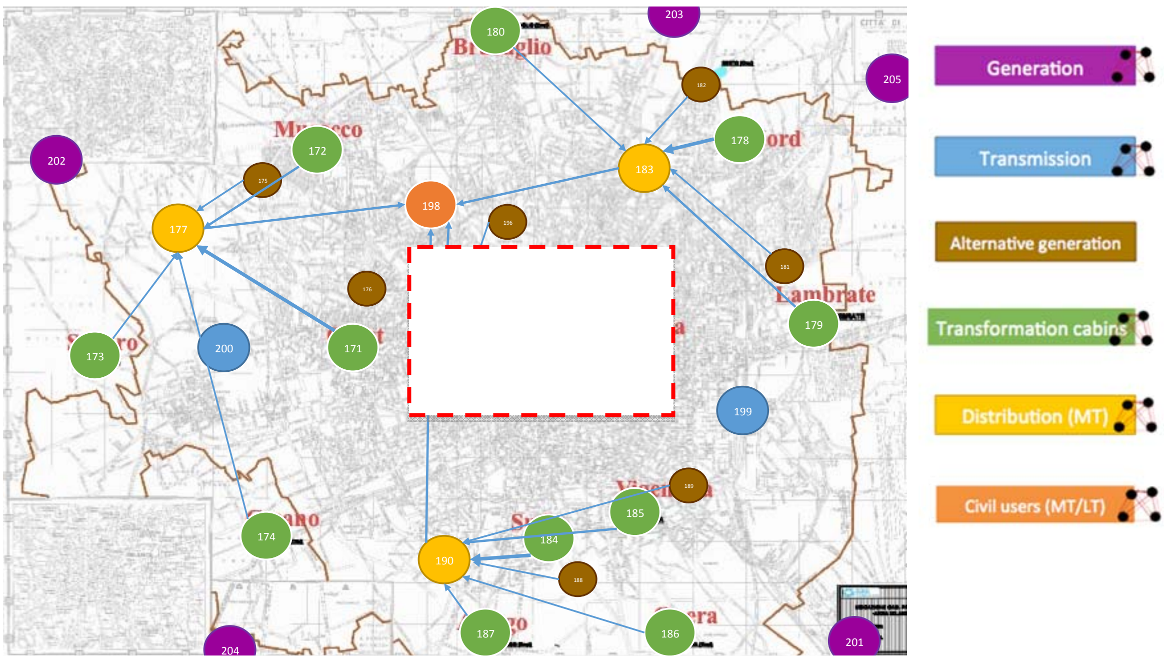


Figure 5 also shows the functional interrelations within the electricity distribution network. In addition to these, as shown in figure 3, there are also other important functional interdependencies with other CI such as railway stations or airports. Functional interdependencies are also used in the DMCI to model information flows or cyber interdependencies within CI. Hence, they are used to model the interdependencies between the electric grid and its control rooms.

Logical interdependencies have also been defined as presented in figure 3, therefore allowing for each subset of transformation cabins to take over each other's demand when one has been damaged. Distribution stations can satisfy demand from other distribution stations in the same exact way. These relations will affect greatly the resilience of the system, as will be seen in the results.

The scenario considered in the pilot application implements a cascading failure that affects the three transformation cabins (nodes 191-193) that supply the distribution station situated in the center of the city (node 197). The threat node then consists of three step signals that hamper each cabin's service capacity for six hours, the first starting at 12:00, second at 14:00 and third and last at 16:00. The response of the electric grid and the effects the event has on other CI can then be quantified and measured, allowing a comprehensive resilience study.

4.2. Analysis and discussion of results

Figure 6 shows the results obtained for the third transformation cabin. The results accurately show how, at 12:00, the cabin first satisfies the demand of the fallen cabin, and how it reaches its full capacity when trying to satisfy the demand from the second fallen cabin. At this point, the three cabins together are no longer able to fully supply its distribution station. The failure then propagates through the electric grid and other CI.

Figure 6: Node's 193 dynamic response.

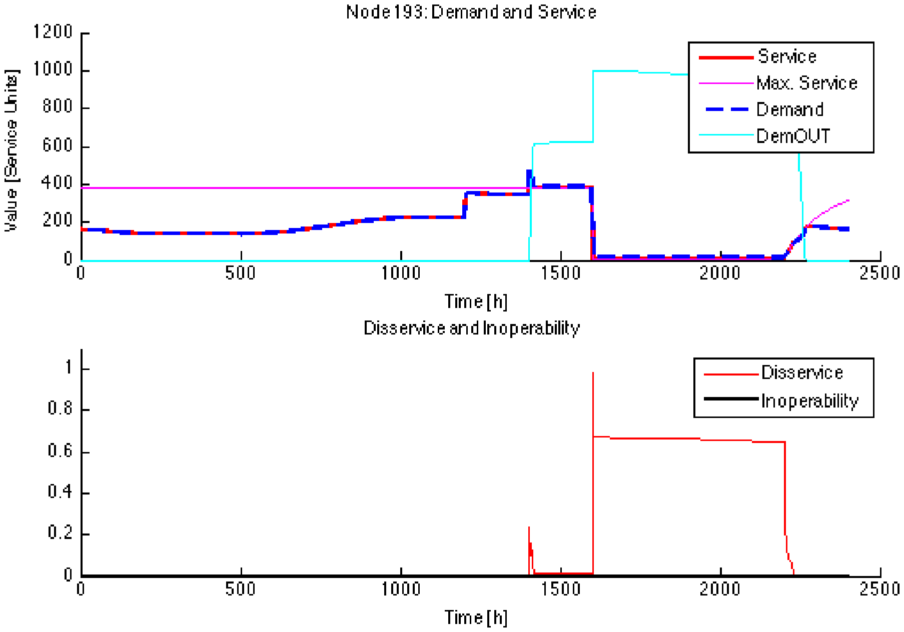
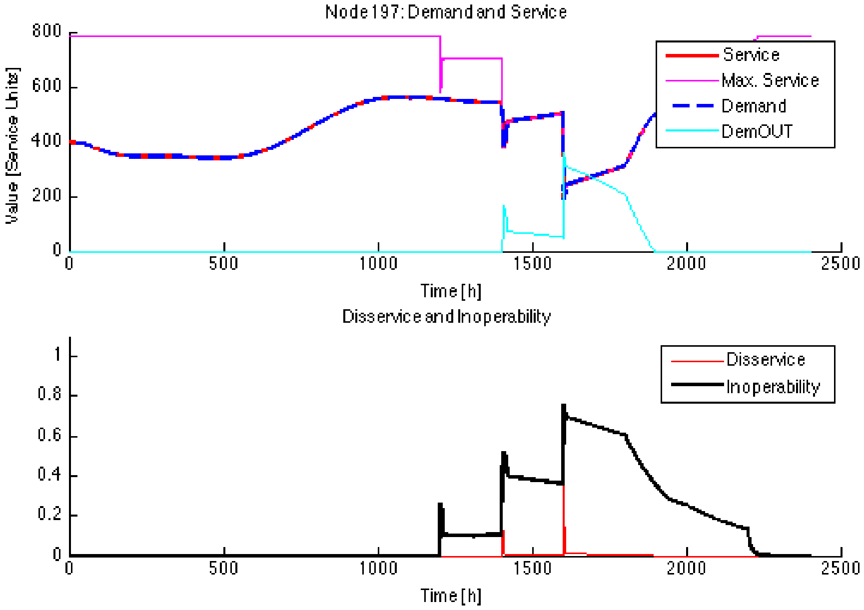


Figure 7 shows the failure of the second and third cabins affect the distribution station's service capacity. However, due to the existing logical interdependencies between distribution stations, the demand shifts allow its disservice to be minimum. This overall behavior accurately resembles that of the modeled system, in which operators rebalance the network to minimize disservice of the grid.
The complete results of the simulation also show several other CI affected in various ways, such as the train station, some national roads and some subway lines, and allow for critical interdependencies between infrastructures to be identified. Furthermore, second order indirect interactions between transportation networks can also be observed.
In conclusion, the results give relevant information regarding the resilience of the electrical network, its new balanced configuration and the detailed dynamic response of parts of the transportation and energy distribution grids. This information offered by the DMCI can then be processed in various ways to show the overall system performance.

Figure 7: Node's 197 dynamic response.



5. CONCLUSIONS

The study provides useful results and original contributions at both methodological and practical levels.
According to Ouyang's classification and review [6], the DMCI model [7] belongs to the category of flow-based network simulation models, considered to be the most capable to capture system dynamics and cover all the types of interdependencies, along with agent-based methods. In the present study we tested the capability of DMCI to be applied also to heterogeneous systems, specifically to analyze interdependencies between electricity and transportation infrastructure systems. Consequently, the major result of the study is a demonstration of the applicability of DMCI to a broad spectrum of CI systems and CIP/R problems. This generalization lies on a proper use of logical interdependencies also between nodes of the same infrastructure (e.g. electricity grid) as a way to model the control logic of the system. In this regard, the simulation results achieved through a pilot application in the metropolitan area of Milan shows the ability of DMCI to simulate and analyze complex cascading effects connected with the dynamic balancing of the transmission and distribution grids.

However, the proposed approach still suffer for some limitations. Despite the pilot application is based on characterization of nodes' performance (disruption, response time and recovery) shaped by real technical and organizational capabilities of operators and public agencies, the contribution (either positive or negative) of real-time decisions and possible changes in organization and strategy are not covered by the simulation model. Finally, further developments are needed to allow a real-time implementation of DMCI as a decision support tool during a large emergency and provide the analyst with a larger set of resilience indexes and enhanced reporting.

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References

[1] "European Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. L 345/75," *Official Journal of the European,* 23 12 2008.

[2] H. A. M. Luiijf, H. Burger and M. Klaver, "Critical Infrastructure Protection in Netherlands: A Quickscan," in *EICAR Conference Best Paper Proceedings*, Copenhagen, 2003.

[3] B. Robert, M. H. Senay, M. E. P. Plamondon and J. P. Sabourin, "Characterization and ranking of links connecting life support networks," in *Public safety and emergency preparedness*, 2003.

[4] S. M. Rinaldi, J. P. Peerenboom and T. Kelly, "Identifying, understansing and analyzing critical infrastructure interdependencies," *IEEE Control System Magazine,* pp. 11-25, 2001.

[5] S. Bouchon, "The vulnerability of interdependent critical infrastructures systems: epistemological and conceptual state-of-art," IPSC Joint Research Centre, Ispra, 2006.

[6] M. Ouyang, "Review on modeling and simulation of interdependent critical infrastructure systems," *Reliability Engineering and System Safety,* vol. 121, pp. 43-60, 2014.

[7] P. Trucco, E. Cagno and M. De Ambroggi, "Dynamic functional modelling of vulnerability and interoperability of Critical Infrastructures," *Reliability Engineering and System Safety,* vol. 105, pp. 51-63, 2012.

[8] S. M. Rinaldi, J. P. Peerenboom and T. Kelly, "Identifying, understanding and analyzing critical infrastructure interdependencies," *IEEE Control System Magazine,* pp. 11-25, 2001.

[9] E. Cagno, P. Trucco and M. De Ambroggi, "Interdependency analysis of CIs in real scenarios," in *Proceedings of ESREL 2011* , Troyes (France), 2011.

[10] M. Beccuti, S. Chiaradonna, F. Di Giandomenico, S. Donatelli, G. Dondossola and G. Franceschinis, "Quantification of dependencies between electrical and information infrastructures," *International Journal of Critical Infrastructure Protection,* vol. 5, no. 1, pp. 14-27, 2012.

[11] I. Eusgeld, C. Nan and S. Dietz, "“System-of-systems” approach for interdependent critical infrastructures," *Reliability Engineering & System Safety,* vol. 96, no. June, pp. 679-686, 2011.

[12] C. Nan, I. Eusgeld and W. Kröger, "Analyzing vulnerabilities between SCADA system and SUC due to interdependencies," *Reliability Engineering & System Safety,* vol. 113, no. May, pp. 76-93, 2013.

[13] I. Onyeji, M. Bazilian and C. Bronk, "Cyber Security and Critical Energy Infrastructure," *The Electricity Journal,* Available online 5 March 2014.

[14] I. L. Pearson, "Smart grid cyber security for Europe," *Energy Policy,* vol. 39, no. 9, pp. 5211-5218, 2011.

[15] S. Gold, "The SCADA challenge: securing critical infrastructure," *Network Security,* no. 8, pp. 18-20, 2009.

[16] A. V. Kumar, K. K. Pandey and D. K. Punia, "Cyber security threats in the power sector: Need for a domain specific regulatory framework in India," *Energy Policy,* vol. 65, no. February, pp. 126-133, 2014.