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ANALYSIS OF A NUCLEAR POWER PLANT FAILURE USING TEMPORAL NETWORKS

Gian Paolo Cimellaro[1], Alessandro Cardoni[1], Stephen Mahin[2]

[1] Department of Structural, Geotechnical & Buinding Engineering (DISEG)
Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129, Torino, ITALY
gianpaolo.cimellaro@polito.it
alessandro.cardoni@studenti.polito.it

[2] Director, NHERI Modeling and Simulation Center (SimCenter)
University of California
CA, USA 94720-1710
mahin@berkeley.edu

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Abstract. *The recent thrust, from both the scientists and policy makers, to increase community resilience identifies lifelines as one of the most important field to intervene on. Lifelines are critical infrastructures which are highly interdependent to each other, and this interdependency can lead to cascading effects when a failure occurs. For this reason the interdependencies should be analyzed also taking into account the time effect. The aim of this paper is to introduce a suitable method for modeling the interdependencies of lifelines even in emergency situations, when the networks change over time. The methodology proposed relies on the Input-output Inoperability Model which has been modified according to the criteria of temporal networks. The critical infrastructures are modeled as graphs and the failure of the elements of the network propagates according to determined rules. Graphs are then interconnected in order to simulate the cascading effects. The Fukushima nuclear power plant disaster has been studied, as it is one of the most complete example of failure due to interdependencies and temporal effects. Results show that the developed methodology applied to a detailed model of the nuclear power plant is able to effectively describe the evolving situation.*

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1 INTRODUCTION

From the civil engineering point of view, lifelines can be grouped into five main categories: electric power, gas and liquid fuels, telecommunications, transportation, and water supply. These are supposed to provide a reliable flow of services and goods essential to the economic, social and political security of a community. The links among different networks increase the potential of cascading failures, which can bring to catastrophic amplification of the damages.

Critical infrastructure systems are dependent and interdependent in multiple ways, where *dependency* refers to the unidirectional relationship and *interdependency* indicates the bidirectional interaction. Several authors have provided different classifications of lifelines interdependencies (Table 1). The first, and still widely accepted, classification is the one given by Rinaldi [1]. According to the period in which it was published, this classification refers only to interdependencies among physical lifelines. Instead, more recent classifications like the one suggested by Cimellaro et al. [2], take into account interdependencies between both physical and no-physical lifelines, and are more appropriate for the evaluation of the overall level of resilience of a community.

Authors	**Types of interdependence**
Rinaldi et al. [1]	Physical, Cyber, Geographic, Logical
Zimmerman [3]	Functional, Spatial
Dudenhoeffer et al. [4]	Physical, Geospatial, Policy, Informational
Wallace et al. [5]	Input, Mutual, Shared, Exclusive, Co-located
Zhang ad Peeta [6]	Functional, Physical, Budgetary, Market and Economic
Cimellaro et al. [2]	Physical, Cyber, Geographical, Policy/Procedural, Societal, Budgetary, Market & Economy

Table 1: Types of interdependencies according to different authors

Different modeling and simulation approaches have been developed to analyze interdependency. They are broadly categorized by the authors in to five types: (a) system dynamics based models, (b) network based models, (c) empirical approaches, (d) agent based models and (e) economic theory based models. A description of these types of models with their advantages and disadvantages can be found in Cimellaro's [7] and in Ouyang's [8] works.

Including time among the types of interdependencies is not an effective way to approach the problem, because both the topology and the type of interdependency vary over time. In fact, none of the previous classifications and models analyzes the effect of the time dimension. Time dependent analyses are required when the temporal inhomogeneity matters and the sequence of events is important. This is usually the case in emergency situations, where the importance of dependencies changes according to the needs of the responders [9]. These aspects should not be ignored, otherwise the system performance can be greatly overestimated.

This paper proposes a new method based on the Input-output Inoperability Method which belongs to the category of the economic theory based models [10]. The classic IIM is a static model and so it is not able to manage dynamic dependencies. Many authors overcame this limitation with extensions of the original IIM [11-13], while in the proposed approach the IIM has been modified using temporal networks. In literature, there are several studies on temporal networks, which are summarized in Holme and Saramäky's work [14]. In this paper, the use of temporal networks is adapted to model the cascading effects between critical infrastructures using a spatial multilayer environment.

2 MODELING THE TIME DIMENSION

Backup systems are still the best practice to guarantee the reliability of an infrastructure during a stress condition. However, to consider the effect of time on the networks, it is required to have a model capable of representing at every time step the current condition of the system. In this section the Input-output Inoperability Method and its modifications are presented.

2.1 Input-output inoperability method and its limitations

The Leontief's input- output (I-O) analysis of economic interdependencies [15] was adapted by Haimes and Jiang [10] to develop the Input-output Inoperability Method. Inoperability is defined by the authors as the inability for a system to perform its intended function. It is quantified by a value between 0 and 1: when the inoperability of an element is 0 it means that it is working at the top of its potentialities, instead when it is 1, it is completely inoperative. These risks of inoperability are propagated between different networks following the interdependency patterns. The Equation describing the IIM is the following:

$$q = \left[I - A \right]^{-1} \cdot c \tag{1}$$

where q is the damage vector which contains the inoperability values for the n infrastructures considered; A is a matrix which describes the interdependence between infrastructures and it is the transpose of the adjacency matrix which describes the topology of the system; I is an identity matrix and c is the scenario vector which include the effects of the perturbation (e.g. natural disasters, man-made attacks, intrinsic failures, etc.) on each infrastructure. The damage vector q is the output of the model and quantifies the level of inoperability of the infrastructures composing the system according to the topology described by the A-matrix. Each element of this matrix quantifies the level of influence of the *j-th* infrastructure on the *i-th* infrastructure. They can be value between 1, complete propagation of the scenario from j to i, and 0, no propagation. The A-matrix represents thus the probability of transferring inoperability across different infrastructures.

To give an example of which are the output of the IIM, the case of a six-node network developed by Valencia [16] is reported. From now onwards it will referred to as Example 1. There are two networks, an electric and a water network, serving three buildings (Figure 1). The hazard considered is infrastructure aging. To measure the impact of individual node decay across the network, the decay score is computed the column summation of the damage vector q of each node i at each time t:

$$dc\_s_i\left(t\right) = \sum_{i=1}^{j} q_i\left(t\right) \tag{2}$$

This approach, applied to a complex infrastructure network, presents three severe limitations: (a) it does not take into account the redundancies of the system; (b) it does not consider the temporal evolution of the system since it is a static model and does not account temporal effects that can disrupt the system; (c) its inputs and outputs are not significant probabilistic quantities.

A simple implementation is suggested to reduce the limitation relative to redundancies. If a new pump house is added in parallel to the first one, the network presents a redundancy. Figure 2 shows the new topology of Example 2.

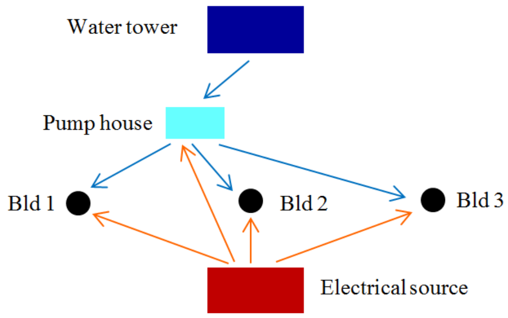

Figure 1: Graph representing Example 1 topology

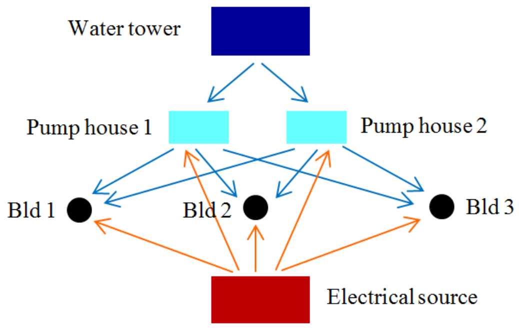

Figure 2: Graph representing Example 2 topology

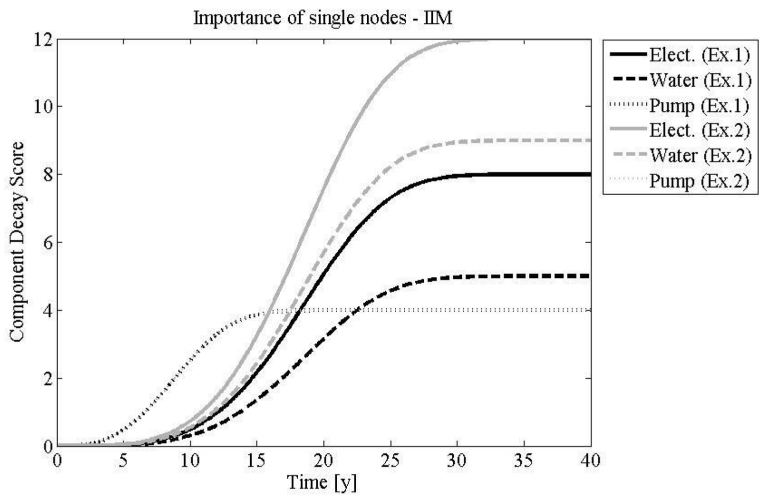

Figure 3: Comparison of decay score of Example 1 and Example 2 using the traditional IIM

It is clear that the performance of the system is improved respect to the previous case because both the pump houses can perform the same work and their simultaneous failure is more unlikely than the failure of just one. We expect that the impact of the water tower and of the electrical source remains the same, while the impact of each of the pump houses decreases. But if we compare the results obtained with the one-pump case (Figure 3), we can see how the expected trends are not present: electrical source and water tower *dc_s* increases and pumps decay score doesn't change.

To solve the problems related to redundancies, probabilities of nodes in parallel can be combined properly. In the previous case, the *dc_s* of electrical source and water tower are increasing because the algorithm sees another node (the new pump) to be fed by them. To avoid this, it is possible to introduce the Series-Parallel Vector:

$$SP = \begin{pmatrix} 1/n_1 \\ 1/n_2 \\ \vdots \\ 1 \end{pmatrix} \tag{3}$$

where n_i is the number of nodes redundant of node *i*. After having expanded it to the n-dimension, it is possible to add it to the damage vector equation:

$$\begin{aligned} SP^* &= SP \times \{1 \quad 1 \quad \cdots \quad 1\}_{1\times n} \\ q_i(t) &= \left[I - A \cdot SP^* \right]^{-1} \cdot c_i \end{aligned} \tag{4}$$

Thanks to this operation, the results of this implementation reflects the initial expectations about redundancies effects (Figure 4).

To represent the performance of the entire system: the system score index is itroduced. It is an adimensional risk index that ranges between 0 ÷ ∞. It is the rating of a system of infra-structures, at the time *t*, as defined in Equation (5):

$$sys\_s(t) = \sum_k \frac{\sum dc\_s_{k,i}(t)}{n_k} \tag{5}$$

where *k* is the type of node (i.e. electrical sources, water towers and pump houses). The final targets (i.e. buildings) are not considered when calculating the *sys_s*. A low value of the *sys_s* indicates that there is a low risk of target nodes' failure, while a high value indicates high risk.

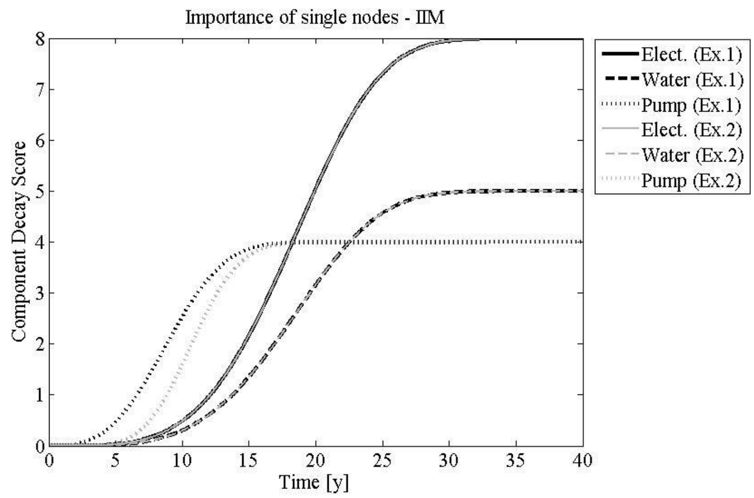

Figure 4: Comparison of decay score of Example 1 and Example 2 using the modified IIM

2.2 Modified input output inoperability method

Many extensions of the model have been proposed such as the Dynamic IIM (DIIM) and the Multi- Regional IIM (MR-IIM). The model presented hereafter tries to overcome some of the limitations of the methodology proposed by Haimes. Graph theory has been used to model the infrastructure networks. The geographical, topological, and flow information of a network can be represented with a graph *G(V, E)* which is formed by a set *V* of vertices, called nodes, and a set *E* of edges. The definition of the nodes depends on the spatial scale of the problem considered which might be an entire infrastructure [17], a sub-system or even a unit. To each node can be attributed specific features such as hierarchy, resistance and au-tonomy, while edges do not have any features assigned, but they are oriented. The edges can link nodes intra-network (i.e. within a specific infrastructure) or inter-networks (i.e. across different infrastructures). Any inter-network link will be specified as Boolean, either 0 or 1. Thus $a_{xi\,yj}$ values will be 0 if the *x-th* node belonging to the i-th infrastructure is dependent node the *y-th* node belonging to the *j-th* infrastructure.

The chain concept is then introduced. A chain is a sequence of nodes from one vertex to another using the edges. The chains of interest are those that connect a source (i.e. a node without inflows) to a sink (i.e. a node without outflows). The task of every source is to feed all the sinks of the network, if it does not, the source is called partial. It is assumed that every node of a chain must have at most one inflow edge, but can have multiple outflow edges. Each of these chains can guarantee the operability of the network, though they are mutually exclusive. The hierarchy of their operation is defined by the design of the infrastructure. There are two possible kind of hierarchy: the source hierarchy corresponds to the rank of priorities for the entry into operation of the sources, the path hierarchy instead corresponds to the rank of priorities for the activation of different possible paths. It is assumed that source hierarchy is stronger than path hierarchy is. This means that if the first chain is not working, the network tries to maintain operation starting from the previous source and inquiring new paths. If no other path is available for that source, then it skips to the following one.

The proposed methodology modifies the IIM deterministic formulation in probabilistic terms, because while the *dc_s* just gives a snapshot of the cascading propagation of inoperability, it does not say anything about the final state of the network. The probability of failure of a single node is obtained by combining the natural hazard with the infrastructure vulnerability and it refers to the status of the node itself after the perturbation. Hereinafter it will be called self-failure probability (P_{sf}) and will substitute the scenario vector *c*. The hazard component is represented by an event vector $E(n \times 1)$ where *n* is the number of nodes in the system. At a given time *t* every node will be disrupted by a natural event. The elements of the vector *E* can be physical quantities such as the *pga, pgv, pgd*, the wave height of a tsunami, the megatons of an explosion, etc.

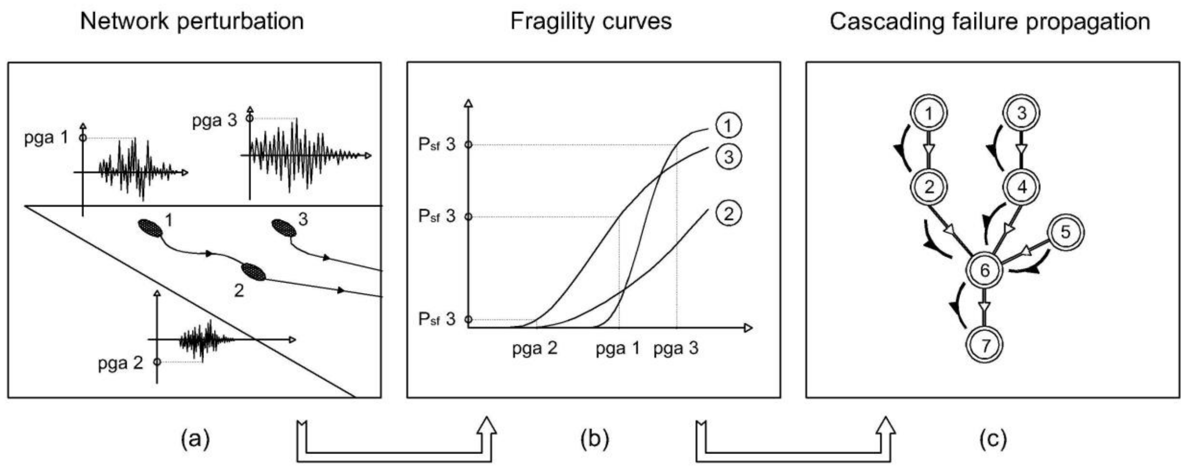

Figure 5: Flowchart of the probabilistic approach. Starting from a network perturbation (a) probabilities of failure of nodes are computed on fragility curves (b) and then propagated according to the topology (c)

These quantities can be different from node to node, because infrastructures usually have a large spatial extension (Figure 5a). Using different *E*-vectors it is possible to approach the problem in probabilistic terms. Each simulation has a weight, which is directly taken from the hazard curves. The vulnerability component of each node is represented by the fragility curves (Figure 5b). Therefore, for each node there are as many fragility curves as the type of hazard considered. The probability of failure P_{sf} of a node is obtained inserting the value of the E-vector in the node fragility curve. The approach proposed by Valencia [16] of summing up the elements of the q-vector to obtain a final score to evaluate the interdependency performances has obvious limitations, because they are not normalized to the dimension of the system. Moreover, the index proposed does not take into account of the benefits given by the redundancies. In the modified IIM proposed, the probability of failure P_f of every node is obtained combining the P_{sf} with the cascading failure probability P_{cf} which is transmitted by the upstream nodes taking into account the ramifications of the system (Figure 5c). In other words, P_f is the probability of failure of each node which is obtained as result of all the disrupting events and the cascading propagation effects.

The more intuitive approach for analyzing a system of infrastructures is solving each network separately and then considering their interaction. Infrastructure networks are shown as layers, which overlap each other and share some nodes. Considering Example 1, the element pump needs both electricity and water. Using layer's visualization, a single node will be projected in the two layers and a virtual edge will link the two projections (Figure 6).

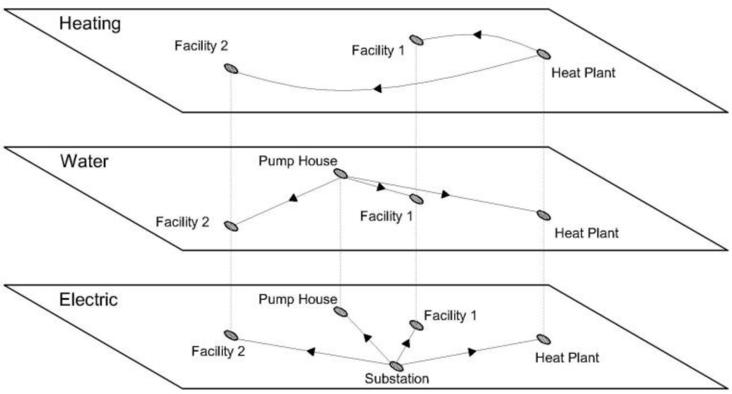

Figure 6: Example of layer subdivision for interdependent networks

This multilayer approach brings many benefits. (a) It discerns the analysis and results of layers and interdependencies and it helps understanding where criticalities are located and which are the tighter and more stressed inter-links. While the evaluation of single infrastructure is mature, the interdependency studies are still at a development stage and inquiring them is the real issue. (b) Moreover, giving the possibility to each infrastructure manager of running the model of a given layer and then control the interaction between the different layers at a higher level, is closer to the professional practice adopted during an emergency response phase. A model which considers all the elements of the system simultaneously will not be used in the real practice, because none has the authority and competences to manage all the data. (c) In the end, informatics tools, like Geographic Information Systems (GIS), in both the emergency response and the risk planning sector, organize data in databases shaped with a layer structure.

Another issue is that the classic IIM can only use square matrices, while the inter-networks matrices are usually rectangular. To overcome this limitation, Valencia [16] suggests the introduction of a I-matrix. These are $n \times m$ matrices, where n is the number of nodes of the *j-th* infrastructure and m the number of nodes of the *i-th* infrastructure, which depends on the *j-th*. The idea is to increase the values of *c*-vector of infrastructure *i*, by adding the *q*-vector computed for the *j-th* network (Equation (6)).

$$c_{j\to i} = I_{j\to i}{}^{T} \cdot q_j + c_i \quad (6)$$

Inserting the output of the first network into the input of the second one is the correct approach for the evaluation of the cascading effects. However, this formulation starts from the same deterministic values of before, so it cannot be considered satisfactory. The current method involves the combination of the P_{cf} of upstream and downstream networks:

$$P^{*}_{cf_i} = \left(I_{j\to i}{}^{T} \cdot P_{cf_j} \right) \cup P_{cf_i} \quad (7)$$

where the P^{*}_{cfi} can be considered cascading-failure probability which incorporates in the node all the information coming from upstream networks and nodes.

Temporal dimension has now to be considered. The first add-on, compared to the traditional static IIM, is the introduction of a timeline $\tau = [t_0, t_1, t_2, \cdots, T]$, where the range $t_0 \div T$ must be extended enough to include all the event. The time step Δt of the elements of the τ-vector represents the time necessary for the propagation of the events across the entire system. The final situation, at the time $\bar{t}$, will be the initial condition at the time $\bar{t} + \Delta t$. Given this timeline, it is clear that to each event must be associated a time of occurrence and that the model must run at every time step. Now the model is not stationary but is composed of temporal networks, denoted $G(t) = G(V, E(t))$. The P_f of nodes changes over time, in accordance with the sequence of events.

The multilayer approach was effective in modelling interdependencies among different networks, but here the networks are mutually exclusive, and not linked. The solution adopted is to pass from bi-dimensional matrixes to a tri-dimensional tensor notation. The topology of every network is now described by an adjacency tensor *A(t)*, whose element are $a_{xiyj}(t)$. Each different temporal layer of *A(t)* represents a possible chain.

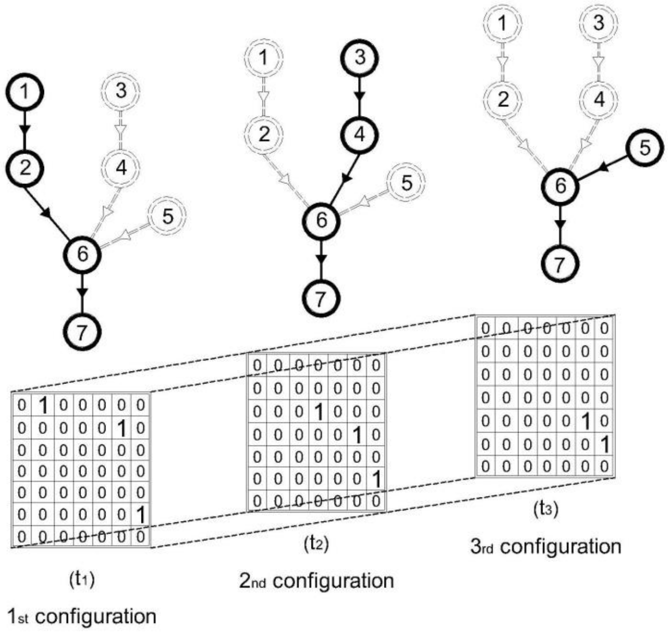

Figure 7: Tensor notation for a network. An adjacency matrix is associated to each of the possible, and mutually exclusive, configurations of the network

To better understand which of the chains is active at the time $\bar{t}$, the probability of occurrence of a specific configuration P_{OCC} is assigned to each layer. This value expresses if the layer is on ($P_{OCC} = 1$), or if is off ($P_{OCC} = 0$) at the considered time step. The condition for being on is that, in the current configuration, target nodes of the network do not fail and that configurations with higher degree of hierarchy are off. Transferring this concept in the probabilistic model means that values of P_{OCC} become probabilities of being active. The sum of the probability of occurrence of a network is $0 \leq \Sigma P_{OCC} \leq 1$ and the value $1 - \Sigma P_{OCC}$ represent the percentage of lost capacity of the network (LoC).

This temporal tensor notation has many advantages compared to static bi-dimensional notation. (a) It is able to describe changes in the topology of the system that usually occurs after individual node failures. (b) The separation of chains in different layers allows the computation of cascading failure responsibility of each node without considering the presence of parallel branches. (c) The P_{OCC} furnishes direct information on the activity of each chain and allows the evaluation of time-related effects, like the autonomy. (d) It is possible to use the value $1 - \Sigma P_{OCC}$ as an index for quantifying the loss of capacity of the network. (e) Varying the topology of the system it is possible to add new layers to existing networks.

3 CASE STUDY

A nuclear power plant is taken as an example to illustrate the methodology, because nuclear power plants depend on extended regional scale infrastructures, which can be analyzed using the IIM, but at the same time have service plants at the local scale. The 2011 Fukushima nuclear power plant disaster has been selected, where it is clear the effect of interdependence and temporal effects. The earthquake and tsunami that struck Japan's Fukushima Daiichi nuclear power station on March 11, 2011, knocked out backup power systems that were needed to cool the reactors at the plant, causing three of them to undergo fuel melting, hydrogen explosions, and radioactive releases. When the earthquake struck, units 1, 2, and 3 were generating electricity and shut down automatically and backup diesel generators started up as designed to supply backup power. However, the subsequent tsunami flooded the electrical switchgear for the diesel generators, causing most AC power in units 1 to 4 to be lost. Only one generator continued operating to cool units 5 and 6.

3.1 Modeling the Fukushima nuclear power plant

The aim is to realize a model of a nuclear power plant equipped with a Boiling Water Reactor (BWR), on the shape of the one present at Fukushima. The topology and data regarding disrupting events affecting the system are inspired to the Fukushima case study, but parameters of the component of the system are generic and taken from the literature.

This work does not model exactly the Unit 1 of Fukushima Daiichi NPP because data are unavailable. However, the plant scheme of the Unit 1 provided by Tokyo Electric Power Company (TEPCO) was used as a reference for building nuclear power plant models. In the scheme there are the electric network, the water network and the steam network. For the purposes of this analysis, the steam network has not been considered by itself but it has been put together with the water one. Cooling circuits are closed. These loops have been modeled with one-direction links from the source to the reactor core. Apart from the water network, which is present at the local/building scale, there is also the electric network, which expands from the regional scale to the local one. The task is to run a performance analysis of all the system serving the reactor core, so all the components important for the success or failure of the reactor cooling have been modeled.

Two different models will be presented: the first simplified, the second more detailed.

The simplified model is shown in Figure 8 and is composed by an electric and a water network. The sources of the electric network are, in order of priority, the external electric network, diesel generators and DC batteries. All these possible configurations converge into a power panel which then feed the pumps of the ordinary water network. The source of the water network is the sea which is considered to have unlimited autonomy, as well as the external electric network is. The first emergency cooling systems consists in the Isolation Condenser (IC), which cools the steam coming from the reactor in a pool and does not need electricity because the flow is gravity-driven. After this, the High Pressure Coolant Injection system (HPCI) can cool the core in emergency condition. It draws water from the Condensate Storage Tank (CST) or from the Suppression Pool (SP) and inject it into the core form reducing the internal pressure. The pump used by this system is steam-driven so it is fed automatically once the plant is started. In conclusion we have three possible configuration for the electric network and four configurations for the water cooling network.

Both the electric and the water networks have connections more complex than the ones presented in the simplified model. Starting from electric sources, the self-sustainment guaranteed by the NPP is introduced. Then every sources, and relative paths, feed particular target nodes and not all of them. The ordinary cooling line, for example, is only feed by the NPP turbine and the off-site AC power, while diesel generators feed the Residual Heat Removal (RHR) cooling system. The IC and HPCI systems, which were considered not dependent on electricity in the simplified model, are now indirectly dependent on it, because their activation is performed by valves which can be remotely controlled only with electricity supply. The DC battery is responsible of the functionality of this valves.

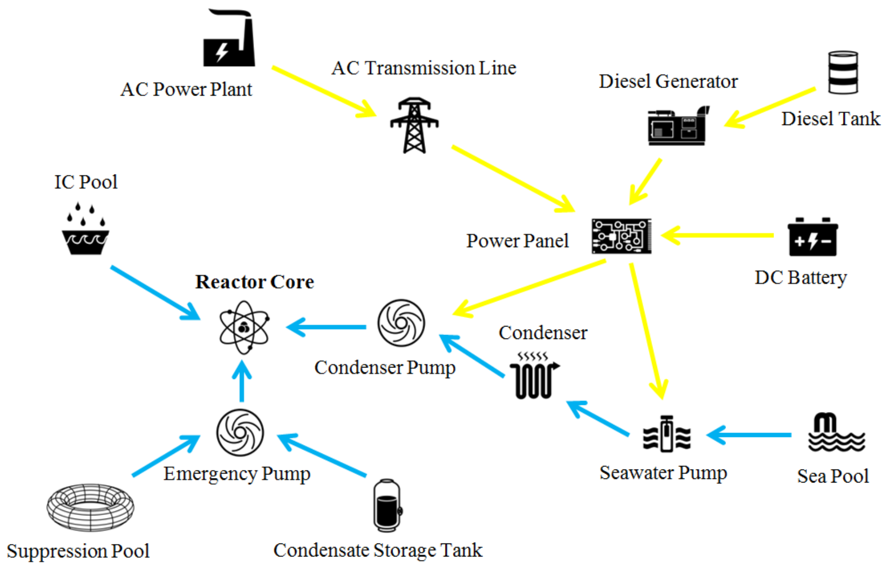

Figure 8: Simplified model for lifelines serving a nuclear power plant

To better model possible human interventions on the system, other three networks have been added: the telecommunication network, the transportation network and the emergency service network. All the layers of this new detailed model are interdependent, as shown in Figure 9. To assemble the event matrix, E-vectors has been positioned at the correct time step, defined in accordance with the timeline of the events occurred at Unit 1. For what concern earthquake and tsunami fragility functions, most of them has been taken from ATC-13 Earthquake damage evaluation data for California [18]. Nevertheless old and generic, these data are still broadly employed in absence of more reliable and updated sources. Other earthquake fragility curves have been taken from the ALA report [19] and from the HAZUS database [20]. Tsunami fragility curves have been considered linear functions between two values obtained from the ATC-13 recommendations and considerations about the robustness of buildings. Autonomy curves instead, have been estimated to be step function where the step is located in correspondence of the nominal value indicated by Hitachi-GE [21].

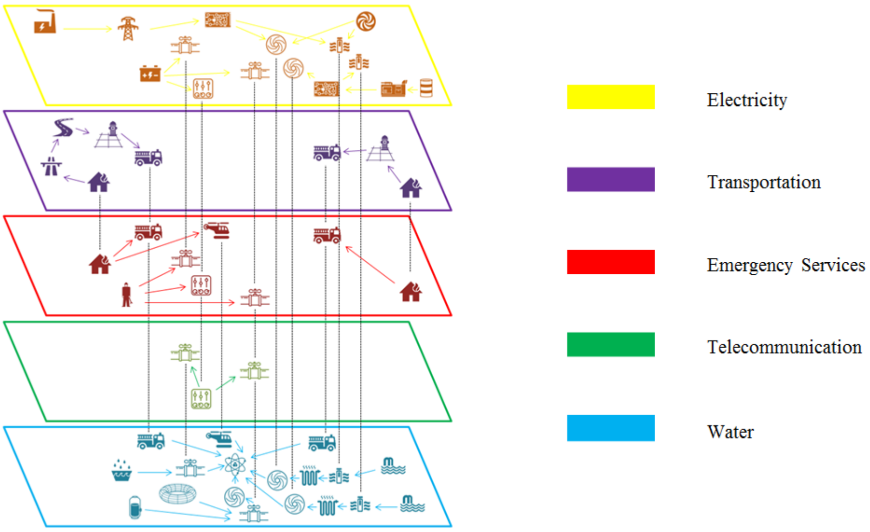

Figure 9: Interdependent layers of the detailed model for lifelines serving a nuclear power plant

3.2 Analysis of the system

This section shows the results relative to the electric network and the water network of both the *simplified model* and the *detailed model* of the NPP modelled. Analysis of the other networks of the detailed model are not reported, because they are not directly comparable with the simplified model, but have been computed since they influence the results of the water network presented.

In the *simplified model* the earthquake is responsible for the shutdown of other power plants and for the collapse of the AC transmission line. This imply the loss of off-site AC power, which represent the first configuration of the electric network. The electric network changes anyway configuration and the power supply is guaranteed to the water network. Other components suffer few damages or no damages. The arrival of the tsunami wave drastically changes the situation. Tanks placed in the NPP apron are swept away as well as the sea pumps. Diesel generators and the ordinary cooling line are out of order. Batteries are damaged too, but there is no need of them anymore since pumps they were feeding are failed. IC backup cooling system, which does not need electricity because works through gravity, is kicked off and the probability of failure of the reactor core cooling is still close to 0. Ten hours after the earthquake, the autonomy of the IC start to decrease and it is substituted by the HPCI system, which does not need electricity because it is equipped with a steam driven pump. As the probability of failure of the IC because of autonomy run out increases, the probability of failure of the reactor core increases as well, because it now relies on the HPCI system, which was potentially damaged by earthquake and the tsunami. Figure 10 summarize these information.

In the *detailed model* the earthquake is responsible for the shutdown of the NPP turbine and of the off-site AC power. AC transmission lines collapse. The loss of off-site AC power propagates the inoperability to the ordinary cooling configuration. Electricity is still provided by diesel generators which feed the RHR system and the control room. Damages caused by the earthquake to emergency cooling systems imply that all of the first three back-up lines have a probability of occurrence $P_{occ} \neq 0$, but anyway the most likely to be active is the RHR. After the tsunami, diesel tanks, CSTs and seawater pumps are completely damaged. The access to the NPP is not usable too, because of the debris deposited by the wave. Rescuers need time to restore a functional access. The water network tries to switch to the IC and HPCI configurations, but to control their valves, DC power is needed. There is a low probability that this is available because the batteries have a relevant probability of failure, so the loss of capacity sharply increases. After three hours, IC valves is manually open and the cooling is provided by the IC, until its autonomy runs out and brings to a complete loss of capacity (Figure 11).

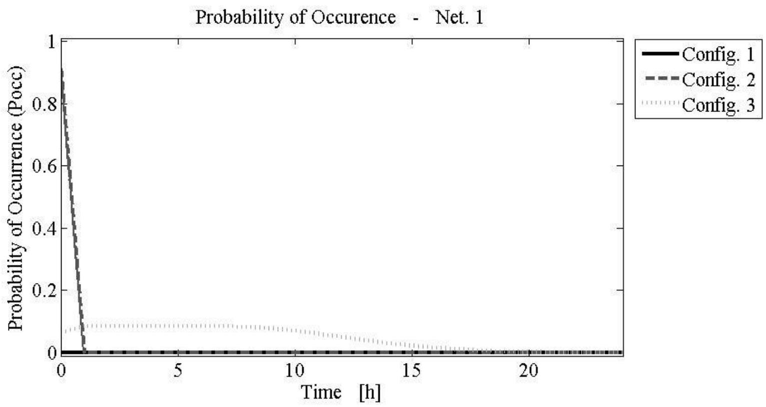

Figure 10: Probability of occurrence for the electric network, simplified model

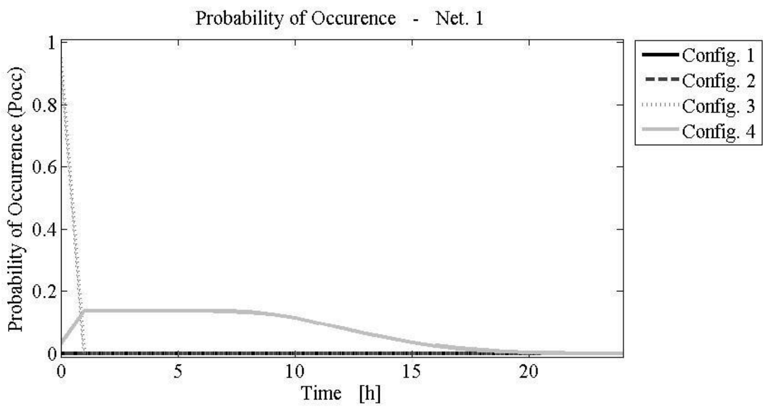

Figure 11: Probability of occurrence for the electric network, detailed model

Results show that both the models can effectively reproduce the ongoing situation for the electric network, while there are some discrepancies in the results obtained for the water network. For the electric network there are not large differences because the only things that change from the two models are the number of power panels and the split of target nodes' supply lines. Target nodes cannot propagate upstream so this implies null effect. In addition to this, the electric network is independent from all of the others, so detailing other networks does not influence it.

4 CONCLUSIONS

In this paper the problem of critical infrastructure networks has been addressed. Disrupting events and major failures of these systems are increasing in number because of the increment of hazards and their exposure, which characterizes modern societies. In addition, the effects of failures are often amplified since lifelines are highly interdependent. To avoid disasters and to reduce costs, it is important to do proper interventions being aware of possible cascading effects.

Therefore, a new methodology has been proposed to model networks that are interdependent to each other and that vary over time after a perturbation of the system. The method is based on the Input-output Inoperability Method, which has been modified with three implementations. First of all a probabilistic approach is used considering hazard curves, fragility curves and probability of failure. Secondly, to visualize the interdependence among networks, a multilayer approach has been adopted. In this way, different networks can be studied separately and then combined together. Finally, a tensor notation is introduced to count the temporal dimension of the network, since interdependencies are not static and may even increase during an emergency condition.

The Fukushima nuclear power plant was selected to test the new method. It has been applied to a simplified model of the nuclear power plant, considering the water distribution network and the electricity network, and also to a detailed model, which considers also other interdependent networks. The results obtained with the simplified model are not reliable in all cases, while the detailed mode is able to represent with a relatively low approximation the situations occurred in that event.

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