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A COMPREHENSIVE METHODOLOGY FOR THE EVALUATION OF INFRASTRUCTURE INTERDEPENDENCIES

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Abstract. *Nowadays infrastructure networks are the basis of life and economy of every community, large or small. These infrastructures have always a certain degree of interdependency among them. This means that when the community is subjected to a shock (earthquake, terrorism, hurricanes, floods, etc.) it is more vulnerable when the degree of interdependency among infrastructures is higher. In this article, after defining a reference nomenclature based on the analysis of the literature in the field and after identifying a total of sixteen type of infrastructures that compose each community: seven core infrastructures (Electricity, Oil delivery, Transportation, Telecommunication, Natural Gas delivery, Water supply, Wastewater treatment) and nine no-core infrastructures (Financial system, Building services, Business, Emergency services, Food supply, Government, Health care, Education, Commodities), we propose a method of analysis of the degree of interdependency among the various members of the community infrastructure. Using a matrix approach, an index is evaluated that takes into account the effect that any infrastructure can induce on another subordinated to it. This index depends on the type of failure that an infrastructure may cause to another one (coupled and uncoupled) and on the number of systems affected. From the matrix display is then possible understanding what are the most important infrastructures for the community and then focus all the efforts to reduce wherever possible the degree of interdependency and/or restore them as quickly as possible in the case of a partial or total disruption.*

1 INTRODUCTION

In literature there are many definitions about the interdependencies that exist among the lifelines of a community. According to President's Commission on Critical Infrastructure Protection (PCCIP) 1997 [1], the *infrastructure* "is a network of interdependent, mostly privately-owned, manmade systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services". *Infrastructure* is also defined as the framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security, the smooth functioning of governments at all levels, and society as a whole (The Clinton Administration's Policy on Critical Infrastructure Protection: Presidential Decision Directive 63)[2].

In the fundamental work of Rinaldi et al.[3], *dependency* is defined as a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other (unidirectional relationship). A distinction of dependencies is also made for different periods in respect to the occurrence of the perturbation (normal operating conditions, which can vary from peak to off-peak conditions, times of severe stress or disruption, or times when repair and restoration activities are under way), as well as between supported and supporting infrastructures. *Interdependency* is defined as a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. In other words, two infrastructures are interdependent when each is dependent on the other, and interdependencies are connections among components in different infrastructures in a general system of systems. Consequently, the risk of failure or deviation from normal operating conditions in one infrastructure can be a function of risk in a second infrastructure if the two are interdependent [4]. The knowledge of the degree of interdependency is necessary to plan a resilient community.

The resilience of a community is a very important parameter. Increasing the resilience of systems is fundamental to ensure the sustainability condition for a community over time. For Mileti [6] "disaster resilient community is a community that can withstand an extreme event, natural or man-made event, with a tolerable level of losses and can take mitigation action consistent with achieving that level of protection". Into 2005 the Multidisciplinary Center for Earthquake Engineering Research (MCEER) provides a comprehensive definition that is particularly useful for assessing resilience of infrastructure systems [7]. Community resilience to hazards is defined as the ability of social units (organizations, communities) to mitigate hazards, contain the effects of hazard-related disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future hazards. The objectives of enhancing disaster resilience are to minimize loss of life, injuries, and economic impacts in short, to minimize any reduction in quality of life due to these hazards. According to Bruneau et al. [7], resilience has been defined as the ability of a system to reduce the chances of a shock, to absorb such a shock if it occurs and to recover quickly after a shock. Resilience of a lifeline can be conceptualized with four dimensions: *Robustness* which is the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality; *Redundancy* that is the system properties that allow for alternate options, choices, and substitutions under stress; *Resourcefulness* which is the capacity to mobilize needed resources and services in emergencies; *Rapidity* that is the speed with which disruption can be overcome and safety, services, and financial stability restored. In Cimellaro et al. [8][9][10] resilience is defined as a normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a period of time T_{LC} (life cycle, life span etc. etc) including the recovery period after damage in an extreme event. The time T_{LC} includes the building recovery time T_{RE} and the business interruption time that is usually smaller compared to the other one. Resilience can be achieved by enhancing the ability of a community's infrastructure, (lifelines and structures), to perform during and after a hazard, as well as through emergency response and strategies that effectively cope with and contain losses and recovery strategies that enable communities to return to levels of pre-disaster functioning (or other acceptable levels) as rapidly as possible [11]. In October 2009, the National Infrastructure Advisory Council [12] defines Infrastructure resilience as "the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event." The NIAC establish resilience as a fundamental concept for sustaining and enhancing infrastructure capability. According to this study, resilience is one of three core concepts within this framework to provide a comprehensive approach to homeland security. Resilience helps to mitigate risk to communities, enhance recovery capabilities, and ensure continuity of essential services and functions. This study also established two core resilience objectives: *Broad-based resilience* which is the "improve capabilities of families, communities, private-sector organizations, and all levels of government to sustain essential services and functions", and *Infrastructure resilience* which "increases the ability of critical infrastructure systems, networks, and functions to withstand and rapidly recover from damage and disruption and adapt to changing conditions".

In this paper, a reference nomenclature based on the analysis of the literature in this field (definition of community, infrastructure, systems, subsystems, units and parts) is proposed. Sixteen types of infrastructures which compose each community are identified: seven core infrastructures (Electricity, Oil delivery, Transportation, Telecommunication, Natural Gas delivery, Water supply, Wastewater treatment) and nine no-core infrastructures (Financial system, Building services, Business, Emergency services, Food supply, Government, Health care, Education, Commodities). Finally a method for the analysis of the degree of interdependency among the infrastructures (lifelines) of a community is proposed.

2 INTERDEPENDENCY

Many authors have tried to clarify the taxonomy in this branch of scientific research [4], but nowadays a unique nomenclature, when it talks about interdependency within a community, does not exist. In this paper, for clearness, will be used the following definitions, as shown in Figure 1:

Community: All of the social and physical infrastructures (or lifelines) which contribute and help to the normal daily life of an organized group of people who live in a given area. (i.e. a nation like Italy).

Infrastructure (lifeline): The set of all the systems that contribute to the creation and operation of a physical or social network within a community. (i.e. national power delivery).

System: A set of sub-systems placed together with a specific order and a specific behavior. (i.e. wind power plant).

Sub-system: A combinations of units which create a machinery or equipment or procedure that have defined and specific characteristics and properties (i.e. wind turbine).

Unit: The set of all components (or parts) assembled with a certain order. A unit is an object or a procedure that, by itself, does not have a unique goal (i.e. the gearbox of the wind turbine).

Part: Is the fundamental element with which you can build a unit (i.e. the ball bearing of the gearbox of the wind turbine).

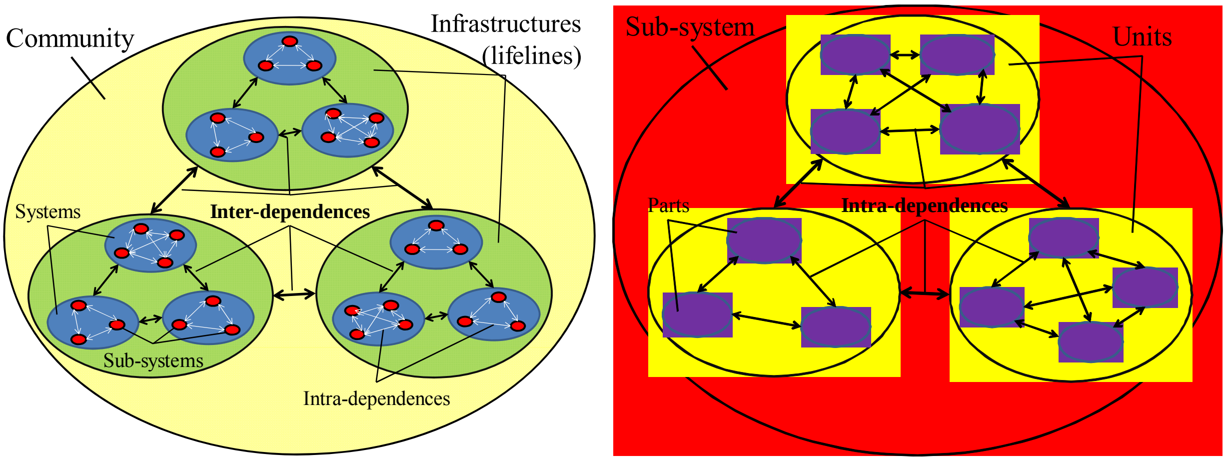

Figure 1. Taxonomy used in this paper.

Also the relationships between the various elements that make up a community does not have a unique definition. In this paper, as shown in Figure 1, is proposed and it is uses the following nomenclature for these internal relationships:

Interdependencies: Bidirectional relationship between the different infrastructures (lifelines) that make up a community and between the different systems that compose an infrastructure (lifeline).

Intradependencies: Bidirectional relationship between the different sub-systems that compose a system, between the different units that make up a sub-system and between the different parts that compose up a unit.

Starting from the literature review proposed by Kongar and Rossetto [13], it has been divided a typical community into sixteen infrastructures (lifelines), which are: *Electricity (Power delivery), Oil delivery, Transportation, Telecommunication, Natural Gas delivery, Water supply, Wastewater treatment, Financial system, Building services, Business, Emergency services, Food supply, Government, Health care, Education, Commodities*. For Kongar and Rossetto [13] there is a core group of infrastructure that are widely recognized as being lifelines: power delivery, telecommunications, transportation, water supply, wastewater treatment, oil delivery and natural gas delivery. The common factor amongst these infrastructure is that although there is some human interfacing to support their operation, they are largely physical systems. In this paper, according to Kongar and Rossetto [13], it has been divided the sixteen infrastructures (lifelines) into two main groups: the *core lifelines* (Electricity, Oil delivery, Transportation, Telecommunication, Natural Gas delivery, Water supply, Wastewater treatment) and the *no-core lifelines* (Financial system, Building services, Business, Emergency services, Food supply, Government, Health care, Education, Commodities).

3 RESILIENCE

Resilience is defined as a normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a period of time T_{LC} (life cycle, life span etc. etc) including the recovery period after damage in an extreme event [8]. In this thesis the resilience of a community will be calculated starting from the restoration curves (or curves of functionality) of lifelines of the community damaged by a natural disaster.

4 TYPE AND EFFECT OF INTERDEPENDENCY

Nowadays there is not a clear classification about the type of interdependencies between infrastructures. Many authors over the years have tried to give their contribution to this problem. Rinaldi et al. [3] and Peerenboom et al. [14] describes four general categories of infrastructure interdependencies: *Physical, Cyber, Geographic* and *Logical interdependency*. For Pederson et al. [15] there are six general categories of infrastructure interdependencies: *Physical, Cyber, Geographic, Logical, Policy/Procedural* and *Societal interdependency*. In the article of Zhang and Peeta [17] the classification of interdependencies among the infrastructure systems is as follows: *Functional*, *Physical*, *Budgetary*, and *Market and Economic interdependency*.

In this paper, as shown in Figure 2, it has chosen the following classification, identifying seven different types of interdependencies [4]:

Physical interdependency: a physical reliance on material flow from one infrastructure to another. Physical dependencies include the reliance on road and rail networks to move crews and equipment.

Cyber interdependency: a reliance on information transfer between infrastructures. Cyber dependencies include the reliance on telecommunications for supervisory control and data acquisition (SCADA) systems and information technology for ecommerce and business systems.

Geographical interdependency: a local environmental event affects components across multiple infrastructures due to physical proximity. Geographical dependencies include, for example, common corridors that natural gas pipelines share with electric power lines and/or telecommunications lines.

Policy/Procedural: An interdependency that exists due to policy or procedure that relates a state or event change in one infrastructure sector component to a subsequent effect on another component. Note that the impact of this event may still exist given the recovery of an asset.

Societal interdependency: The interdependencies or influences that an infrastructure component event may have on societal factors such as public opinion, public confidence, fear, and cultural issues. Even if no physical linkage or relationship exists, consequences from events in one infrastructure may impact other infrastructures. This influence may also be time sensitive and decay over time from the original event grows.

Budgetary interdependency. “Many infrastructure systems involve some level of public financing, especially under a centrally-controlled economy or during disaster recovery, leading to resource allocation budget interdependencies.”

Market & Economy interdependency. “Shared market resources imply that all systems are interacting sectors in the same economic system. Another manifestation of this interdependency is that these infrastructure systems serve the same end users who determine the final demand for each commodity/service subject to budget constraints. Further interdependencies exist due to the shared regulatory environment where the government agencies may control and impact the individual systems through policy, legislation or financial means such as taxation or investment. An example is how fuel prices can affect both the supply and demand sides of transportation, which in turn can affect the supply and demand for fuel."

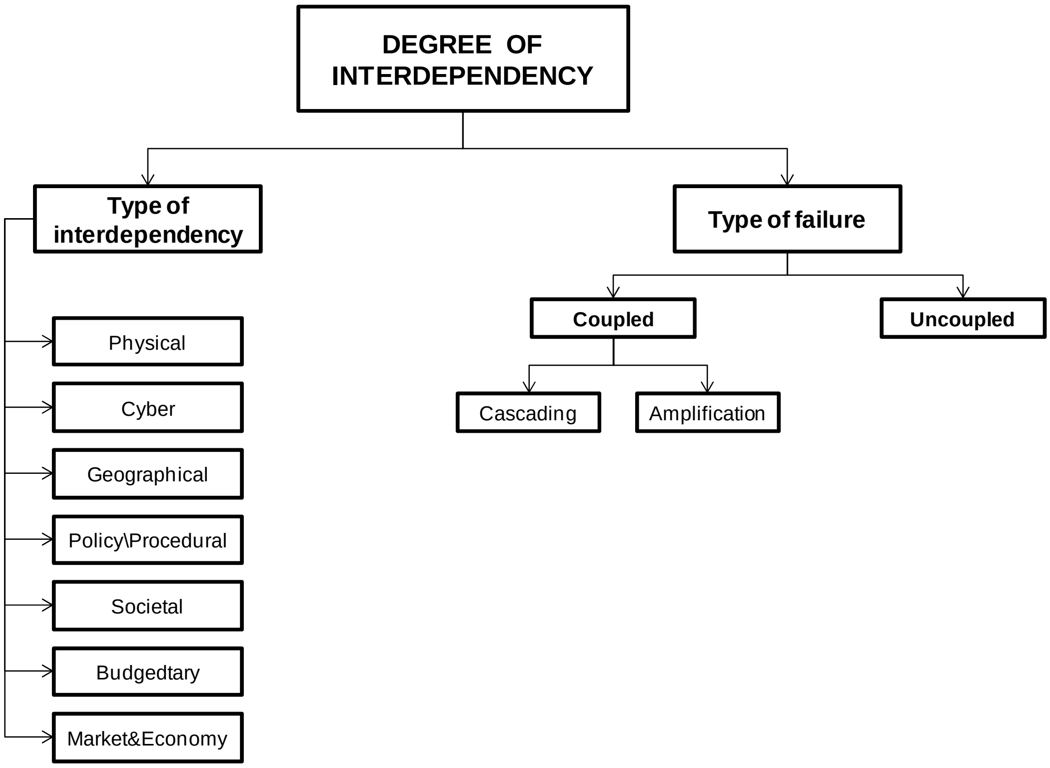

Figure 2. Interdependency index: dependencies on type of interdependency and on type of failure.

In addition to the type of interdependency is useful to understand which is the type of failure that undergoes a lifeline. As shown in Figure 2, the type of failure is classified as follows:

Coupled failure: A drop of functionality of an infrastructure, due to a single perturbation (damaging event) on the community, causes the fall of functionality in at least one other lifeline. If this drop of functionality takes place at the same time for both lifelines, this failure is called *Cascading failure* (Figure 3), while if this drop of functionality takes place in this two lifelines (at least) with a certain time-delay, this failure is called *Amplification failure* (Figure 4)

Uncoupled failure: A drop of functionality of one infrastructure, due to a single perturbation (damaging event) on the community, do not cause any failure in other infrastructures. There is no propagation of failure among infrastructures (Figure 5).

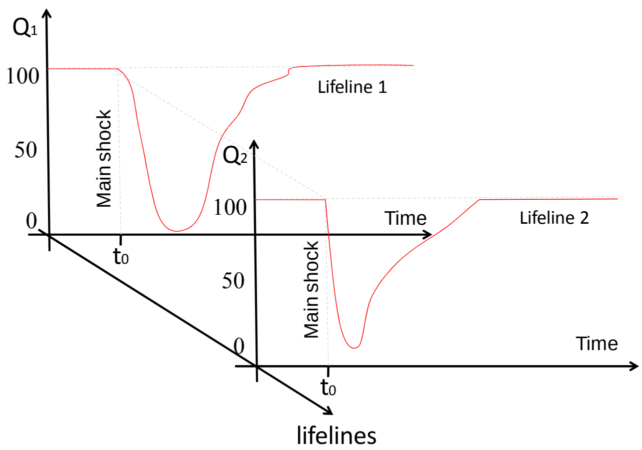

Figure 3. *Coupled failure*: example of *Cascading failure*

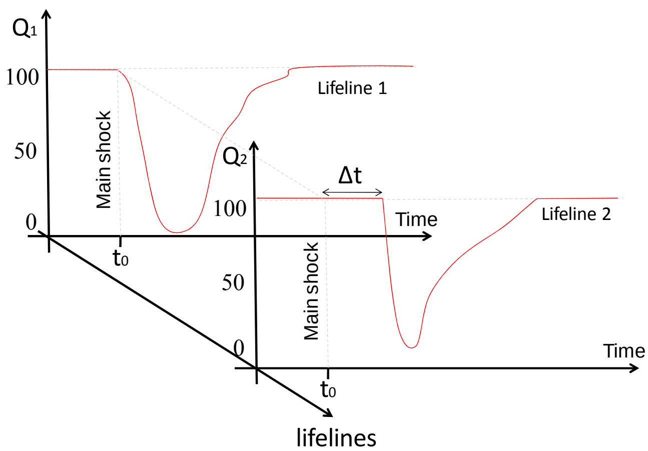

Figure 4. *Coupled failure*: example of *Amplification failure*. The failure in the second lifeline occurs with a time-delay Δt.

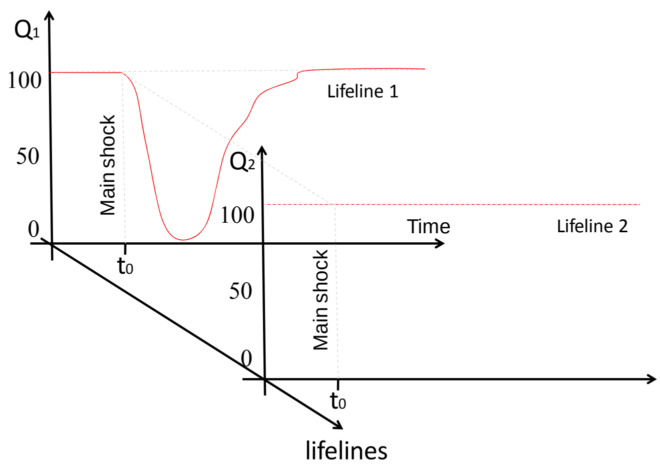

Figure 5. Example of *Uncoupled failure*.

The degree of interdependency is a function, as well as the *type of interdependence* and the *type of failure*, also of the *importance factor* of each lifeline's system (which depends on the degree of interconnection and the degree of importance that has the system with respect to the other lifelines in the community). If the *importance factor* is wide [small], the degree of interdependency must be high [low]. This classification has been carried out so that the degree of interdependency results hazard-uncorrelated and damage-uncorrelated, so that it can be used as a basis for any kind of scenario arising from any damaging event (earthquake, hurricane, flood, fire, tsunami, Electromagnetic pulse attack (EMP), etc.).

5 FRAMEWORK FOR THE EVALUATION OF THE DEGREE OF INTERDEPENDENCY AMONG LIFELINES

For the evaluation of the degree of interdependency, it is necessary to calculate, at first, the degree of dependence which has the first lifeline on the second and the degree of dependence which has the second lifeline on the first. To do this, it is necessary to analyze the dependencies at systems level, subdividing each lifeline in systems and assigning a value of dependence of each system of the lifeline under consideration, on all the sixteen lifelines that make up the community [5]. The degree of dependency of each system of a lifeline with respect to another lifeline can be evaluated using the procedure proposed below. This procedure is a framework useful to focus on the interdependencies that are presents in a community, analyzing it at the level of systems.

- Divide each lifeline in systems, according to the definition of *system* given previously (Figure 1).
- Divide the systems into seven groups correspondents on the seven types of interdependency as defined in Figure 2 (*Physical, Cyber, Geographic, Policy/Procedural*, *Societal, Budgetary*, *Market & Economy interdependency).*
- For each system and for each group defined at the point above, is assigned a degree of interdependency with respect to the sixteen lifelines of the community. This degree of interdependency is a function of two values assigned at every system of the lifeline. The first value is assigned as a function of the type of failure (*Cascading, Amplification, Uncoupled*); the second value is assigned as a function of the *importance factor* that has each lifeline's system.
- The values obtained at the end of the third point are combined into a single value which is the degree of interdependency among the two lifelines under examination. The result is one degree of interdependency for each group defined in the second point of this procedure (seven values for each pair of lifelines). So, finally there are seven matrices of the degree of interdependency, one for each type of interdependency.
- The seven matrices obtained at point 4 are assembled together using different weight coefficients for different types of interdependency (Figure 6) [15]. Further studies will be able to address the problem of the determination of the weight coefficients to be assigned at each type of interdependency.

The matrix thus obtained is the interdependency index matrix of lifelines (S) which is a 16x16 matrix in which each row and each column represents a lifeline. The values are arranged such that the interdependence value *S* at row i and column j ($S_{i,j}$) is the value of interdependence of the lifeline on the column j with respect to the lifeline on the row i. By placing the interdependencies in this way, it can find additional information from the matrix just been built; according to Paton and Johnston [18], adding the data per row in the matrix $S_{i,j}$ it can obtain a number that indicates the level of leadership (*Leadership index* in Figure 6) that the lifeline of that row has respect to the other fifteen lifelines of the community; adding the data per column in the matrix $S_{i,j}$ it can obtain a number that indicates the level of subordination (*Subordination index* in Figure 6) that the lifeline of that column has respect to the other fifteen lifelines of the community.

	can affects ↓ in this points:																
the ↓	Electricity	Oil delivery	Transportation	Telecomunication	Natural Gas delivery	Water supply	Wastewater tratment	Financial system	Building services	Business	Emergency services	Food supply	Government	Health care	Education	Commodities	Leadership index
Electricity	**1**	1	0,6	1	1	0,6	0,6	0,6	0,6	1	0,6	1	1	0,6	0,3	0,6	**12,1**
Oil delivery	0,6	**1**	0,6	0,3	0,3	0,3	0,3	0,6	0,6	0,6	0,6	0,6	0,6			0,6	**7,6**
Transportation	0,3	0,6	**1**		0,6			0,6	0,6	1	1	1	0,6	0,6	0,3	1	**9,2**
Telecomunication	0,3	0,3	0,3	**1**	0,3	0,3	0,3	1		1	1	0,6	1	0,3		0,3	**8**
Natural Gas delivery	0,6		0,3		**1**			0,6	0,3	0,6	0,6	0,6	0,6	0,3	0,3	0,3	**6,1**
Water supply	0,6	0,3		0,3	0,3	**1**		0,3	1	0,6	0,6	1	0,6	0,6	0,6	0,6	**8,4**
Wastewater tratment		0,3			0,3	0,6	**1**		0,3	0,6	0,3	0,3	0,3	0,6		0,3	**4,9**
Financial system	0,3	0,3	0,6	0,3	0,3	0,3	0,3	**1**	0,6	1	0,3	0,6	1	0,3		1	**8,2**
Building services	0,3	0,3	0,6	0,3	0,3	0,3	0,3	0,6	**1**	0,6	0,6		0,3			0,6	**6,1**
Business	0,3	0,6	1	0,6	0,6	0,3	0,3	1	0,6	**1**		0,6	1			1	**8,9**
Emergency services	0,6	0,6	0,6	0,6	0,6	0,6		1	0,3	1	**1**	1	1	1	0,6		**10,5**
Food supply	0,3	0,3	0,6		0,3	1	0,3	1	0,3	1	0,6	**1**	1	0,6	0,6	0,3	**9,2**
Government	0,6	0,6	0,6	0,6	0,6	0,6	0,6	1	0,6	1	1	1	**1**	1	1	0,6	**12,4**
Health care			0,3					0,3	0,3	0,3	1	0,6	1	**1**	0,3	0,3	**5,4**
Education	0,3	0,3	0,3	0,3	0,3	0,3	0,3	1	0,3	0,6	1	0,3	1	0,6	**1**	0,3	**8,2**
Commodities	0,3	0,3	1	0,3	0,3	0,3	0,3	1	0,6	1	0,3	0,3	1	0,3		**1**	**8,3**
Index of subordination (dependence)	**6,4**	**6,8**	**8,4**	**5,6**	**7,1**	**6,5**	**4,6**	**11,6**	**8,0**	**12,9**	**10,5**	**10,5**	**13,0**	**7,8**	**5,0**	**8,8**	

Figure 6. Community interdependency matrix. In yellow are highlighted the core lifelines interdependency matrix

The lifeline that has the highest value of *Leadership index* is the one on which pay the greatest attention, because if its functionality falls, the functionality of the community decreases dramatically. To increase the resilience of the community, this lifeline must have the lowest vulnerability to any kind of hazard. Available resources must be concentrated for the improvement of this lifeline or for the reduction of the degree of dependence of other lifelines of the one in question, (for example using redundant networks, accumulators, etc..). The lifeline that has the highest value of *Subordination index* is the one that has the greatest dependence on other lifelines within the community. If the community suffers damage, this lifeline is the first that suffer the effects of propagation of the damage due to the interdependencies, even if, at first, it does not suffer damages. To increase the resilience of the community, available resources must be concentrated for the improvement of this lifeline. This improvement must be a reduction of the dependencies of this lifeline on the others (for example using redundant networks, accumulators, etc.). Every effort must be aimed to achieve that the interdependencies between lifelines of the community are the lowest possible. To do this it defines three situations, in which the community can be found, using the matrix of interdependency index $S_{i,j}$ previously defined. Is defined as (Figure 7):

Very vulnerable community (VVC) the community in which the matrix of interdependency (S) is a matrix in which every values is equal to 1.

Ideal community (IC) the community in which the matrix of interdependency (S) is a matrix in which the values on the diagonal are 1, while the other values are 0. In this community there is only self-dependence, while the interdependence between the different lifelines disappears.

Typical community (TC) all of the others situations between VVC and IC.

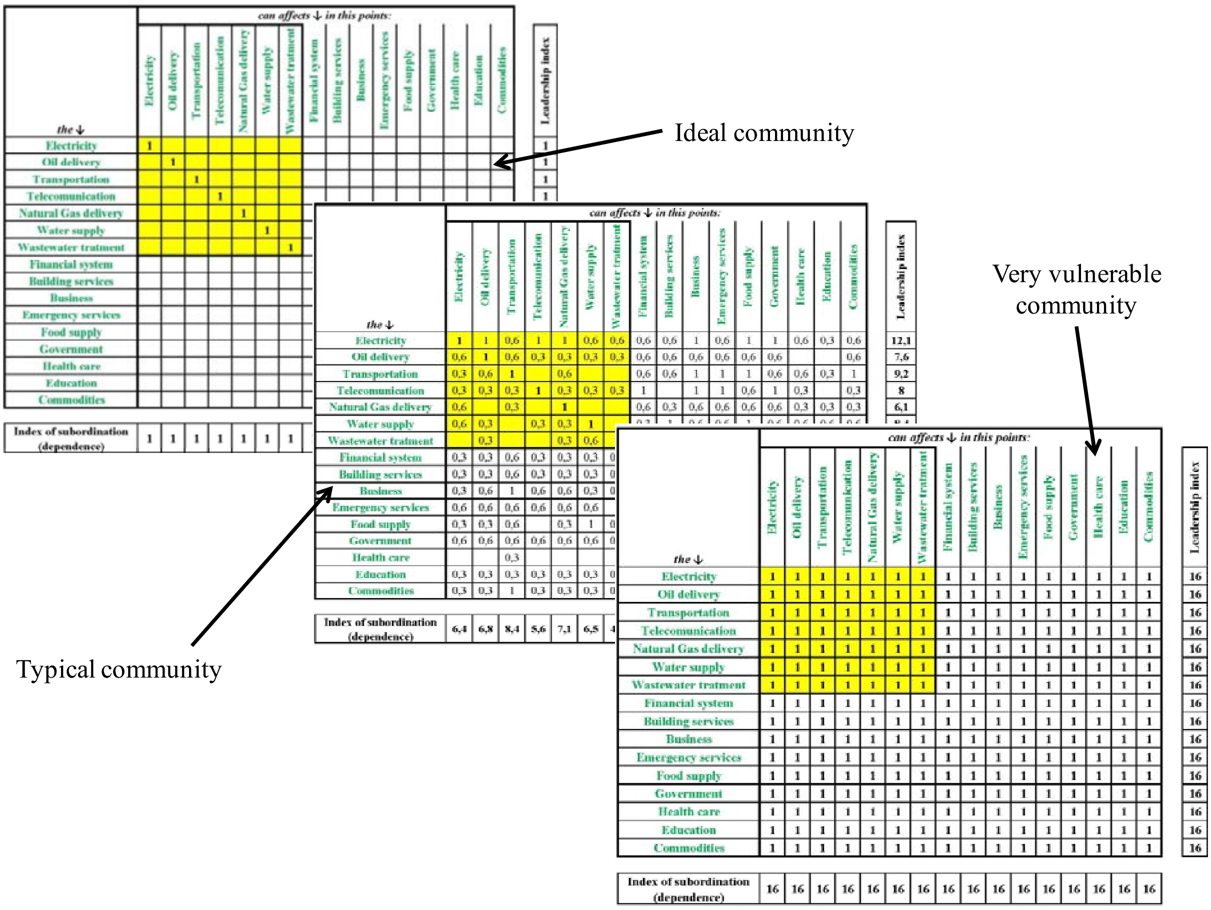

Figure 7. Infrastructures interdependencies matrix. In yellow are highlighted the core lifelines interdependency matrix

If it is necessary, the evaluation of the interdependency can be more detailed with the decomposition of the systems that make up a lifeline, into different sub-systems. The interdependency index matrix can be evaluate with the same procedure shown previously, but now the result is the interdependency index matrix of the systems of two specific lifelines. In Figure 8 is shown how a single value into the interdependency index matrix of the community can be exploded into a matrix of interdependency among two specific lifelines, thus reaching a higher level of detail . This type of analysis is much more expensive, both in terms of time and in terms of cost but it can be more realistic, because going into detail, it is easier to find the interdependencies and it is also possible to compute in a more realistic way. The level of detail for the calculation of the interdependency index matrix can be chosen based on the knowledge that one can about the community and its lifelines, systems, sub-system, units and parts.

the ↓ / can affects ↓ in this points:	Electricity	Oil delivery	Transportation	Telecommunication	Natural Gas delivery	Water supply	Wastewater tratment	Financial system	Building services	Business	Emergency services	Food supply	Government	Health care	Education	Commodities	Leadership index
Electricity	1	1	0,6	1	1	0,6	0,6	0,6	0,6	1	0,6	1	1	0,6	0,3	0,6	12,1
Oil delivery	0,6	1	0,6	0,3	0,3	0,3	0,3	0,6	0,6	0,6	0,6	0,6	0,6			0,6	7,6
Transportation	0,3	0,6	1		0,6			0,6	0,6	1	1	1	0,6	0,6	0,3	1	9,2
Telecomunication	0,3	0,3	0,3	1	0,3	0,3	0,3	1		1	1	0,6	1	0,3		0,3	8
Natural Gas delivery	0,6		0,3		1			0,6	0,3	0,6	0,6	0,6	0,6	0,3	0,3	0,3	6,1
Water supply	0,6	0,3		0,3	0,3	1		0,3	1	0,6	0,6	1	0,6	0,6	0,6	0,6	8,4
Wastewater tratment		0,3			0,3	0,6	1		0,3	0,6	0,3	0,3	0,3	0,6		0,3	4,9
Financial system	0,3	0,3	0,6	0,3	0,3	0,3	0,3	1	0,6	1	0,3	0,6	1	0,3		1	8,2
Building services	0,3	0,3	0,6	0,3	0,3	0,3	0,3	0,6	1	0,6	0,6		0,3			0,6	6,1
Business	0,3	0,6	1	0,6	0,6	0,3	0,3	1	0,6	1		0,6	1			1	8,9
Emergency services	0,6	0,6	0,6	0,6	0,6	0,6		1	0,3	1	1	1	1	1	0,6		10,5
Food supply	0,3	0,3	0,6		0,3	1	0,3	1	0,3	1	0,6	1	1	0,6	0,6	0,3	9,2
Government	0,6	0,6	0,6	0,6	0,6	0,6	0,6	1	0,6	1	1	1	1	1	1	0,6	12,4
Health care			0,3					0,3	0,3	0,3	1	0,6	1	1	0,3	0,3	5,4
Education	0,3	0,3	0,3	0,3	0,3	0,3	0,3	1	0,3	0,6	1	0,3	1	0,6	1	0,3	8,2
Commodities	0,3	0,3	1	0,3	0,3	0,3	0,3	1	0,6	1	0,3	0,3	1	0,3		1	8,3
Index of subordination (dependence)	6,4	6,8	8,4	5,6	7,1	6,5	4,6	11,6	8,0	12,9	10,5	10,5	13,0	7,8	5,0	8,8	

the ↓ / can affects ↓ in this points:	Road	Rail	Air	Maritime transport	Leadership index
Road	1	0,6	0,6	0,3	2,5
Rail	0,6	1	0,6	0,6	2,8
Air	0,3	0,3	1	0,3	1,9
Maritime transport	0,3	0,6	0,3	1	2,2
Index of subordination (dependence)	2,2	2,5	2,5	2,2	

Figure 8. Interdependency matrix of systems. In yellow are highlighted the core lifelines interdependency matrix.

Each number into the interdependency index matrix can change over time. These variations can be positive or negative and, often, may be due to the normal management of the community; some of these reasons are listed below:

- Improving of the lifelines functionality (positive variation)
- Reduction of lifelines vulnerability (positive variation)
- Creation of a certain redundancy degree among lifelines (positive variation)
- Creation of stocks and emergency systems (positive variation)
- Aging (negative variation)
- Negative human intervention on the lifeline (negative variation)
- etc.

Positive [negative] variation is referred to an improving [worsening] of the global response of the community, reducing [increasing] the degree of interdependency for at least one lifeline.

The degree of interdependency can change through the time when human interventions are performed or because of aging effects, but they are not dependent on the magnitude or type of disaster faced. If the magnitude of an extreme event increases only the "effects" of interdependency increase, but the degree of interdependency which is a property of the community remains the same.

6 A CASE STUDY: FUKUSHIMA DAIICHI NUCLEAR POWER PLANT DISASTER

Fukushima Daiichi (Daiichi means “first”), was a multi-reactor nuclear power plant in the prefecture of Fukushima of Japan (Figure 9a). The Fukushima I Nuclear Power Plant consists of six, boiling water reactors (BWR, Figure 12) designed by General Electric driving electrical generators with a combined power of 4700 MW, making Fukushima I one of the 25 largest nuclear power stations in the world.

(a)

(b)

Figure 9. Fukushima Daiichi Nuclear Power Plant before (a) and after (b) the disaster

When the earthquake occurred on March 11th, 2011, the reactors on Units 1, 2, and 3 were operating, but those on Units 4, 5, and 6 had already been shut down for periodic inspection. Units 1, 2 and 3 underwent an automatic shutdown, called “SCRAM”, when the earthquake struck. When the reactors are shutdown, the plant does not to generate electricity anymore. TEPCO reported that one of the two connections to off-site power for reactors 3 also failed so 13 on-site emergency diesel generators began to powered the plant's cooling and control systems.

The earthquake was followed by a tsunami with waves between (13÷15)m maximum height which arrived arriving approximately 50 minutes after the earthquake. The waves topped the 5.70m plant's seawall, flood the basement of the turbine buildings and disabled the emergency diesel generators located there at approximately 15:41 local time. At this point, TEPCO notified authorities, as required by law, of a "First level emergency".

The Fukushima Daini plant (Daini means “second”), which was also struck by the tsunami, incorporated design changes which improved its resistance to flooding and it sustained less damage. Generators and related electrical distribution equipment were located in the water-tight reactor building, so that power from the grid was used by midnight. Seawater pumps for cooling were protected from flooding, and although 3 of 4 failed in the tsunami, they were able to be restored in service. Furthermore they were three additional backup generators for Unit 2 and 4 that were placed in new buildings located on the hillside.

All six reactors were connected to these generators, but the switching stations that sent power from these backup generators to the reactors' cooling systems for Units 1 through 5 were still in the poorly protected turbine buildings. The three generators on the hillside were operational after the tsunami. If the switching stations had been moved to inside the reactor buildings or to other flood-proof locations, power would have been provided by these generators to the reactors' cooling systems. After the diesel generators located in the turbine buildings failed, emergency power for control systems was supplied by batteries that were designed to last about eight hours. Further batteries and mobile generators were dispatched to the site, delayed by poor road conditions, therefore the first did not arrived at the site until 21:00 JST of March 11^{th} , almost six hours after the tsunami struck. The attempts to connect the mobile generators to the water pumps were eventually interrupted after numerous attempts, as the connection point in the Turbine Hall basement was flooded and because of difficulties in finding suitable cables. Below is reported the time schedule of the events that arise after the main shock (until five days after the event). The time is given in Japan Standard Time (JST) which is UTC plus nine hours:

2011, March 11^{th}

- 14:46: A 9.0 magnitude earthquake strikes off the coast of Honshu Island at a depth of about 24 kilometers. The Fukushima I power plant's nuclear reactors 1, 2, and 3 are automatically shut down by the vibrations. Nuclear reactors 4, 5, and 6 were undergoing routine maintenance and were not operating, (reactor 4 was defueled in November 2010). The vibration has the additional effect of causing the power plant to be cut off from the Japanese electricity grid, however, backup diesel generators activated to continue cooling the reactors. Tokyo Electric Power Company (TEPCO), the plant's operator, finds that units 1 and 2 are not operating correctly and notifies the proper officials.
- 14:52: Emergency cooling system of reactor 1, which is capable of running without external power, turns on automatically.
- 15:03: Emergency cooling system of reactor 1 is manually shut down.
- 15:27: The first tsunami strikes the plant (Figure 10).

(a)

(b)

Figure 10. The first tsunami strikes the seawalls (a). Flooding of the plant (b) the tsunami had a height of about 14 meters

- 15:30: The emergency condenser designed to cool the steam inside the pressure vessel of the reactor 1 fails.
- 15:46: A 14 meters tsunami, unleashed by the earthquake, overtops the seawall designed to protect the plant from a tsunami of 5.7 meters, inundating the Fukushima facility and disabling the backup diesel generators (all but one of which were housed underground) and washing away their fuel tanks. With the loss of all electrical power supply, the low-pressure core spray, the residual heat removal and low-pressure coolant injection system main pumps, and the automatic depressurization systems all failed (most of the emergency core cooling system). Only the steam-powered pump systems (isolation condenser in reactor 1, high-pressure coolant injection and reactor core isolation cooling system in reactors 2 and 3 remained available. Later, as the temperature rose, a system started that used steam-powered pumps and battery-powered valves.

- 16:00: The Nuclear and Industrial Safety Agency of Japan (NISA) initiates an emergency headquarters in an attempt to gather information on the 55 nuclear reactors in Japan. There is no report that radiation was detected outside power-plant borders.
- 18:00: The falling water level in reactor 1 reaches the top of the fuel, and the core temperature starts climbing.
- 18:18: Emergency cooling system of reactor 1 is once again back on.
- 19:03: Prime Minister Naoto Kan declares a nuclear emergency status announced by Yukio Edano, Chief Cabinet officer in Japan. Japanese government officials try to comfort the people of Japan by telling them that the proper procedures are being undertaken. They also announce that no radioactive leaks have been detected.
- 19:30: The fuel in reactor 1 becomes fully exposed above the water surface, and fuel damage in the central core begins soon after.
- 21:00: An evacuation order is issued by the government to persons within a radius of 3 kilometers from the Fukushima I station. Those within a radius of 10 kilometers are told that they can remain in their homes, and carry on with regular activities, until told otherwise. TEPCO announces that the pressure inside reactor unit 1 of Fukushima I is more than twice normal levels.

2011, March 12th

- 02:44: Emergency battery power for the high pressure core-flooder system (HPCFS) for reactor 3 runs out.
- 04:15: Fuel rods in reactor 3 are exposed.
- 05:30: Despite the high risk of hydrogen (produced from the water in the containment vessel) igniting after combining with oxygen from water or in the atmosphere, and in order to release some of the pressure inside the reactor at Fukushima I unit 1, the decision is taken to vent some of the steam (which contained a small amount of radioactive material) into the air within the metal container building surrounding the unit.
- 05:50: Fresh water injection into reactor 1 is started.
- 06:50: Although unknown at the time, the core of reactor 1 has now completely melted and falls to the bottom of the reactor pressure vessel.
- 10:09: TEPCO confirms that a small amount of vapor has been released into the air to release pressure in reactor unit 1 at Fukushima I.
- 10:58: Pressure still remains too high inside reactor unit 2 at Fukushima I. In order to alleviate some of this pressure, a consensus is reached to once more vent radioactive vapor into the air.
- 14:50: Fresh water injection into reactor 1 is stopped.
- 15:30: Evacuation of residents within 3 km of Fukushima II and within 10 km of Fukushima I are underway.
- 15:36: There is a massive explosion in the outer structure of unit 1. The concrete building surrounding the steel reactor vessel collapses as a result of the explosion; however no damage is believed to have been sustained to the reactor itself. Four workers are injured(Figure 11).
- 19:00: Sea water injection into reactor 1 is started. TEPCO orders Daiichi to stop seawater injection at 19:25, but Daiichi plant boss Masao Yoshida orders workers to continue with the seawater injection.
- 21:40: The evacuation zone around Fukushima I is extended to 20 km, while the evacuation zone around Fukushima II is extended to 10 km.

Figure 11. Massive explosion of Unit 1

To release pressure within reactor unit 1 at Fukushima I, steam is released out of the unit into the air. This steam contains water vapor, hydrogen, oxygen and some radioactive material, mostly tritium and nitrogen-16. TEPCO engineers decided to directly inject sea water inside the pressure vessel of the reactors by means of the mobile trucks of the firemen. The pressure relief was also necessary to allow the firemen to inject seawater into the reactors vessels.

2011, March 13th

- 02:42: The high pressure coolant injection system for reactor 3 stops and, shortly thereafter, the water level within the reactor starts falling.
- 07:00: The water level in reactor 3 reaches the top of the fuel.
- 09:00: Core damage starts occurring in reactor 3.

A partial meltdown was reported to be possible at unit 3. At 13:00 JST reactors 1 and 3 are vented to release overpressure and then re-filled with water and boric acid for cooling, and to inhibit further nuclear reactions. Unit 2 was possibly suffering a lower than normal water level, but was thought to be stable; although pressure inside the containment vessel was high. The Japan Atomic Energy Agency announced that it was rating the situation at unit 1 as level 4 (an accident with local consequences) on the International Nuclear and Radiological Event Scale.

2011, March 14th

- 11:01: The unit 3 reactor building explodes, injuring six workers. According to TEPCO there was no release of radioactive material beyond that already being vented, but total damage affected the water supply to unit 2.
- 13:15: The reactor core isolation cooling system for reactor 2 stops and, shortly afterwards, the water level within the reactor starts falling.
- 15:00: A major part of the fuel in reactor 3 drops to the bottom of the reactor pressure vessel.
- 18:00: The water level in reactor 2 reaches the top of the fuel.
- 20:00: Core damage starts occurring in reactor 2.

The president of the French nuclear safety authority (ASN), said that the accident should be rated as a 5 (an accident with wider consequences) or even a 6 (a serious accident) on INES.

2011, March 15th

- 06:00 An explosion damaged the 4th floor rooftop area of the Unit 4 reactor as well as part of the adjacent Unit 3.
- 11:00: A second explosion of reactor 3
- 20:00: A majority of the fuel in reactor 2 drops to the bottom of the reactor pressure vessel.

Damage to the temporary cooling systems on unit 2 from the explosion in unit 3, plus problems with its venting system, meant that water could not be added to the extent that unit 2 was in the most severe condition of the three reactors. An explosion in the "pressure suppression room" causes some damage to containment system of unit 2. A fire breaks out at unit 4. Radiation levels at the plant rise significantly but subsequently fall. Radiation equivalent dose rates of 400 milli Sieverts per hour (400 mSv/h) are observed at one location in the vicinity of Unit 3.

To operate safely, a nuclear power plant needs to be cooled continuously, especially when the reactor is shut down, because reactors continues to generate heat also when the chain reaction is stopped because of the radioactive decay of unstable isotopes and fission products created by this process. The decay heat in the reactor core decreases over several days. Nuclear fuel rods that have reached cold shutdown temperatures typically require another several years of water cooling in a spent fuel pool.

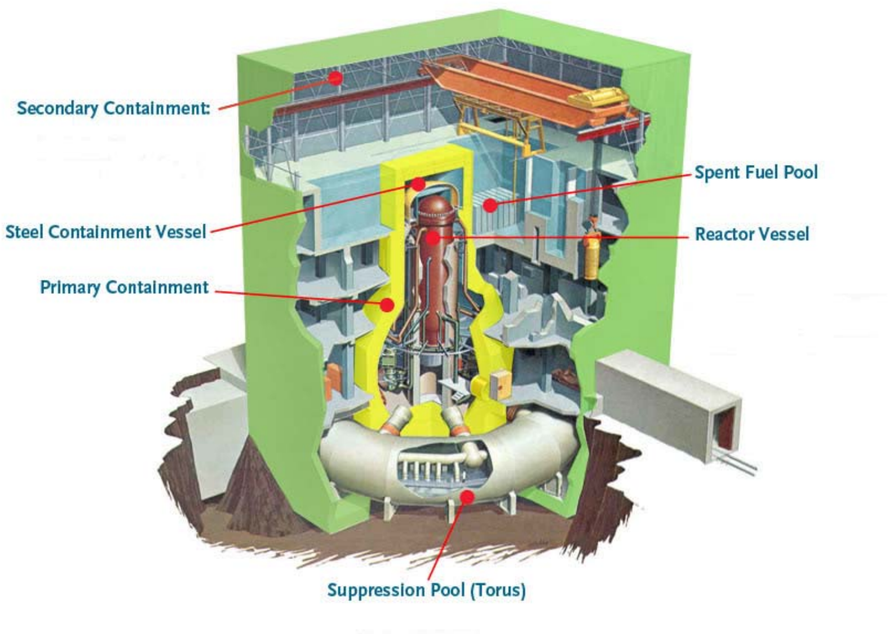

Figure 12. Design of a Boiling Water Reactor (BWR)

The reason that cooling is so essential for a nuclear reactor, is that many of the internal components and fuel assembly cladding is made from zircaloy[1] [[1]Zirconium alloys are solid solutions of zirconium or other metals, a common subgroup having the trade mark Zircaloy.

Zirconium has very low absorption cross-section of thermal neutron, high hardness, ductility and corrosion resistance]. At normal operating temperatures (of approximately 300 degrees Celsius), zircaloy is inert. However, when heated to above 500 degrees celsius in the presence of steam, zircaloy undergoes an exothermic reaction where the zircaloy oxidizes, and produces free hydrogen gas. The reaction between the zirconium cladding and the fuel can also lower the melting point of the fuel and thus speed up a core melt. The result of this problem is shown in Figure 9b.

To circulate cooling water when the reactor is shut down and not producing electricity, cooling pumps can be powered by other units on-site, by other units off-site through the grid, or by diesel generators. In addition, boiling water reactors have steam-turbine driven emergency core cooling systems that can be directly operated by steam still being produced after a reactor shutdown, which can inject water directly into the reactor. Steam turbines results in less dependence on emergency generators, but steam turbines only operate so long as the reactor is producing steam. Some electrical power, provided by batteries, is needed to operate the valves and monitoring systems. Is the fail of the cooling system that had lead to the nuclear disaster in the Fukushima Daiichi nuclear power plant.

6.1 Interdependency that occurred

To analyze the interdependencies it is necessary to frame the Fukushima Daiichi nuclear power plant in the model presented in the previous paragraphs. In this case the community is *Japan*, The infrastructure (lifeline) on which the power plant are insert is *Electricity* (Power delivery) and the Fukushima Daiichi nuclear power plant is a *system* of this lifeline.

From the time line listed above, it is clear that the *system* "Fukushima Daiichi nuclear power plant" is interdependent with the *Electricity* (for the external power supply when the reactor are shout down in order to guarantee the operability of cooling system) and the *Transportation* (more precisely with the *system* "road network" for the emergency supply of materials) lifelines. Going into details, in order to use the information on the nuclear disaster that are mentioned above to evaluate a certain degree of interdependency, it is necessary to subdivide the system "Fukushima Daiichi nuclear power plant") into the following main sub-systems and list which interdependency appeared after the tsunami: The main sub-systems are: *Reactors*, *Cooling system of Reactors*, *Emergency generator for the cooling system of Reactors*, *Control room of the power plant*, *Tsunami barriers*, *Automatically shutdown system of Reactors*.

Based on the time line listed above, are appeared the following physical intradependencies:

- *Amplifying failure* of reactors if the cooling systems fail
- *Amplifying failure* of reactors if the emergency generators fail
- *Cascading failure* of cooling systems if the emergency generators fail
- *Amplifying failure* of reactors if the tsunami barriers fail
- *Cascading failure* of cooling systems if the tsunami barriers fail
- *Cascading failure* of emergency generators if the tsunami barriers fail
- *Cascading failure* of reactors caused by the automatically shutdown system of reactors

The matrix of physical intradependency among this sub-systems can made in the following way (Table 1), where R = reactors, CS = cooling systems, EG = emergency generators for the cooling system, CR = control room, TB = tsunami barriers, ASS = automatically shutdown systems.

	R	CS	EG	TB	ASS
R	1	-	-	-	-
CS	A	1	-	-	-
EG	A	C	1	-	-
TB	A	C	C	1	-
ASS	C	-	-	-	1

Table 1. Physical intradependency index matrix among the sub-systems of the Fukushima Daiichi power plant system.

where A = Amplifying failure and C = Cascading failure. 1 is the maximum possible degree of intradependency. Based on the same time line, the following cyber intradependencies are appearing:

- *Cascading failure* of automatically shutdown system of reactors if the control room fail;
- *Cascading failure* of emergency generators if the control room fail;
- *Cascading failure* of emergency generators if the automatically shutdown system fail;

The matrix of cyber intradependency among these sub-systems is shown in Table 2:

	CR	ASS	EG
CR	1	C	C
ASS	-	1	C
EG	-	-	1

Table 2. Cyber intradependency index matrix among the sub-systems of the Fukushima Daiichi power plant system.

Give an univocal numerical value at every intradependencies can not be possible, because of the complexity of the examined system. However a complex system like the Fukushima Daiichi nuclear power plant can be easy framed into the method proposed in this paper.

Recently Cimellaro et al. [19] have proposed a method based on the use of the restoration curves of some lifelines. The authors developed an equation based on the cross correlation function among two restoration curved (after a normalization, logarithmically transformation and second differentiation of the restoration curves) with which they calculate the interdependency index *S*. This kind of method lead to a simplified evaluation of the interdependency index, because the index *S* come from two restoration curves that contain, without distinction, information derived from the single systems of which they are composed. The method proposed in this paper is more detailed respect to the one proposed Cimellaro et al. [19], because the evaluation of the interdependency index are based on the interdependency that arise among different systems (or sub-systems). Every system contribute to the final value of interdependency and it is possible to identify which are the systems that cause more problems of interdependency into a lifeline in order to adequate or improve only that systems, focusing only the available resources in order to maximize the ratio between invested money and reduction of interdependency. However the method proposed by Cimellaro et al. [19] can give a numerical quantification (although simplified, because all the information about systems interdependencies are into a single restoration curve) of the interdependency index. The method proposed in this paper can be a useful framework to analyze the interdependency that arises among different lifelines and different systems into a community.

7 CONCLUSIONS

In this paper, it is proposed a framework to evaluate the degree of interdependency between infrastructures (lifelines) of a community. A reference nomenclature is defined while sixteen infrastructures that compose each community are identified: seven core infrastructure (*Electricity, Oil delivery, Transportation, Telecommunication, Natural Gas delivery, Water supply, Wastewater treatment*) and nine no-core infrastructure (*Financial system, Building services, Business, Emergency services, Food supply, Government, Health care, Education, Commodities*). Each lifeline is divided in *systems*, while interdependencies are subdivided in seven types (*Physical, Cyber, Geographic, Policy/Procedural, Societal, Budgetary, Market & Economy interdependency*).

For each system and for each type of interdependency, it is assigned a degree of interdependency, which is function of two values assigned at every type of lifeline. The first value is function of the type of failure (*Cascading, Amplification, Uncoupled*). The second value is function of the *importance factor* that each lifeline's system has. Lifeline interdependencies are evaluated combining the values of interdependency of systems in which the different lifelines have been divided.

Finally there are seven types of interdependencies for each lifeline's pair, which are organized in seven interdependencies matrices. The degree of interdependency (or interdependency index) can assume values between 0 and 1, where 0 represents the absence of interdependency, while 1 represents maximum interdependency between the two infrastructures. For each matrix, it can be evaluate the *Leadership index* that the lifeline of a given row has with respect to the other fifteen lifelines identified in the community (obtained adding per row the data in the interdependency matrix $S_{i,j}$) and the *Subordination index* that the lifeline of a given column has with respect to the other fifteen lifelines in the community (obtained adding per column the data in the interdependency matrix $S_{i,j}$). The lifeline that has the highest value of *Leadership index* is the most important lifeline in the community which requires a higher level of attention, because if its functionality fails, the performances of the community decrease dramatically. The lifeline that has the highest value of *Subordination index* is the one that has the greatest dependency on the other lifelines within the community. If the community suffers damage, this lifeline is the first that suffers the effects of propagation of the damage due to the interdependencies, even if, it does not suffer damages. It is important to know which the lifeline with the maximum Leadership index is, and which the lifeline with the maximum *Subordination index* is, in order to focus all the available resources of the community on these two lifelines, in order to do not waste resources and optimizing the global response of the community in terms of interdependency and sustainability. Finally as case study, it is analyzed the 2011, March 11th, Fukushima Daiichi nuclear power plant disaster. Some sub-system intradependencies are highlighted and are placed into the proposed framework. Further studies are necessary in order to give a numerical quantification of interdependencies at the *system* level (local level), in the same manner which is proposed at a global level when infrastructures are considered as global entities.

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