Towards an integrated vulnerability and resilience analysis for underground infrastructures

Enrico Cagno[1], Ottavio Grande[1] and Paolo Trucco[1]
[1] *Department of Management, Economics and Industrial Engineering - Politecnico di Milano*
Piazza Leonardo da Vinci, 32 – I-20133 Milano, ITALY
ottavio.grande@polimi.it

Abstract. The growing complexity of modern society is fostering great attention to the issue of the continuity of critical services and related infrastructures. The underlying processes and physical components of a specific service delivery (e.g. electric power or water) reveal many dependencies both technical and non technical. The paper presents an integrated methodology for vulnerability and resilience analysis for underground infrastructures, i.e. a societal risk analysis of the failures of underground services for an urban area. Based on the use of a hybrid approach, the proposed methodology breaks down the area under analysis into sub-areas and assesses the dependencies among sub-areas both in terms of interoperability, damage propagation of critical infrastructures and target zoned-description. The methodology demonstrates clear advantage in terms of resilience analysis, more consistent with the "zoned" nature of failures of the underground infrastructures. A case study, dealing with the interoperability and damage propagation analysis of the underground infrastructures of a Northern Italy town, will be presented for this purpose. A resilience analysis of the "system of systems" (i.e. multiple underground infrastructures) can be performed through the proposed methodology, evaluating the internal characteristics of the system able to mitigate or amplify the impact of local failures and thus the capability to assure service continuity after such failures. Finally a strategy for risk mitigation is proposed in order to maintain the minimum level of service.

1 INTRODUCTION

The growing complexity of modern society is fostering great attention to the issue of the continuity of critical services and related infrastructures. The underlying processes and physical components responsible for a single specific service supply delivery (e.g. electric power or water) reveal many dependencies both technical and non technical; indeed large infrastructures are constituted of many equipments and connections that can fail, reducing the service level and/or propagating damages (domino effect), also to other infrastructures. In order to minimize the effects of these events the development of solutions for the protection of such infrastructures (Critical Infrastructures Protection, CIP) is needed. Moreover the growing complexity and vulnerability of critical infrastructures (e.g. electrical power, oil&gas distribution, transport system, water, healthcare, ICT) requires an innovative approach for mitigating the occurrence of disruptions and service interruptions, and also the definition of measures for evaluating the effects on vulnerable targets (e.g. population, buildings, other services). In literature the complex interactions between infrastructures, targets and objects hit by the failure have been described (Luiif, 2003, Kroger, 2008) and quantitative approaches, for the analysis of real cases of disruption and related effects, have been proposed (Haimes & Jiang, 2001; Haimes, 2005, Setola, 2007). The paper presents an integrated approach for vulnerability and resilience analysis for underground infrastructures, i.e. a societal risk analysis of the failures of underground services for an urban area. The approach is based on the detailed study of 1) domino-effects – considering both interoperability and damage propagation aspects - for the components of a single infrastructure and for a given set of infrastructures interoperated and/or belonging to the same area; 2) risk and vulnerability analysis of a given area, in order to better understand the effects and the interrelations of interoperability and damage propagation; 3) identification of guidelines for interventions to improve the overall system resilience. The proposed hybrid approach – (inter)dependency analysis (Luiif, 2003, p. 10) and area risk analysis (Egidi et al., 1995, p. 80 - 83) - breaks down the area under analysis into sub-areas and assesses the dependencies among sub-areas both in terms of interoperability of critical infrastructures and damage propagation, and zoned-description of target. The methodology demonstrates clear advantage in terms of resilience analysis, more consistent with the “zoned” nature of failures of the underground infrastructures. A case study -developed in collaboration with Lombardy Region, its Technical Development Center (CESTEC) and Cremona Municipality - dealing with the interoperability and damage propagation analysis of the underground infrastructures of the historical urban area of Cremona (Cagno et al., 2008), will be presented for this purpose.

2 TOWARDS AN INTEGRATED METHOD: INTEROPERABILITY AND AREA RISK ANALYSIS

A significant number of methods has been presented in literature for conducting vulnerability assessments and risk management of critical infrastructures and, in particular, different approaches for the design (Lian et al., 2007) and the resilience analysis of existing networks (Moore, 2005) have been developed. Recently, Snediker (Snediker 2008) focused his contribution on the understanding of how disruptions can impact network operation with a topological approach, and, consequently, proposed a DSS for evaluating different disruption scenarios. Otherwise a risk approach can be used for identifying critical systems (Aven, 2008): a risk informed approach actually seems to be a better instrument for combining vulnerabilities and expected consequences with uncertainties and phenomenological studies of the processes. Moreover an approach useful for describing the whole effect of a disruption could be focused not only on the risk from an individual infrastructure but also the risk associated with the increasing interdependence between several infrastructures operating over the same area. Identifying, understanding, and analyzing such interdependencies are significant challenges. The described steps are the followings: 1) analysis of the most critical infrastructures, based onto cartographic and GIS data; 2) assessment of the main interoperability and damage propagation effects and vulnerability of the principal targets; 3) evaluation of system resilience and possible interventions for risk mitigation.

2.1 Interoperability analysis

The principal quantitative approach to interoperability analysis of infrastructure is derived from the Leontief model (Leontief, 1986). It considers a set of components of a product (or a service infrastructure) and defines a linear equation able to study the inoperability of the system according to the relations that exist between the different components and interactions with the external environment. The inoperability of a system is defined as the "inability of the system to perform its intended functions" (Haimes & Jiang, 2001, p. 2). Thus the variable describing the inoperability is assumed to be a continuous variable evaluated between 0 and 1, with 0 corresponding to a flawless operable system state and 1 corresponding to the system being completely inoperable. For the proposed model, we consider a system consisting of n critical complex interconnected infrastructures, with the output being their level of inoperability that can be triggered by one or multiple failures due to complexity, accidents, or terrorist attacks, assumed as the external inputs.

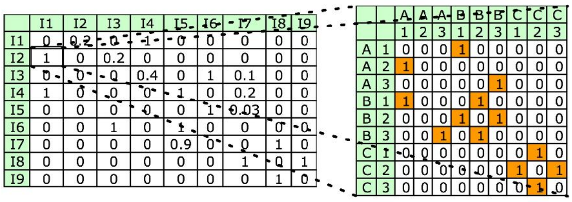
The modelling of the problem is obtained through the so-called "Leontief matrix" that, given n infrastructures, is made up of n x n elements $a_{ij.}$ The inoperability induced on the system by external cause c_k, also taking into account the presence of dependencies and interdependencies among the different component, is described in equation (1):

$$X(k+1)=AX(k)+c \tag{1}$$

Where $X \in R^n$ and $C \in R^n$ are vectors composed, respectively, of the level of inoperability and external failures associated with each one of the n different infrastructures considered in the scenario. $A \in R^n$ is the Leontief matrix, in which entry a_{ij} represents the level of influence that the inoperability of the i-th infrastructure has on the j-th one. Notice that in the model, $a_{ij} = 1$ means that the j-th infrastructure is completely dependent on the i-th one, because a given service reduction in the latter will directly induce an equal level of service degradation into the j-th one. Applicative examples and results of this approach are reported in literature (Setola, 2007; Haimes & Jiang, 2001, p. 5-8).

2.2 Area and Vulnerability analysis as an extension of the interoperability model

In the Leontief's approach it is apparent the absence of some geographical or topological aspects: the Leontief matrix cannot refer the results to a particular zone, area or node of the networked infrastructures; on the other side the importance of these details is crucial for managing a disruption or estimate the extension of service interruptions. To solve the problem we propose an integration of the Input-Output Inoperability Model (IIM) (Haimes & Jiang, 2001, p. 2-4) with the well known topological and area risk methods (Albert et al., 2004; Egidi et al., 1995;). To this end two different Leontief-like matrixes were used for 1) single infrastructure analysis and 2) interdependency analysis between two or more infrastructures. Indeed, the first step is similar to the conventional IIM, but the matrix (Figure 1) contains in rows and columns the references to specific geographical areas, in that a coefficient indicates the level of dependency: this matrix contains the value 1 if exists a potential failure propagation between two adjacent areas of the same infrastructure (e.g. in case of the physical continuity of a pipeline).



	I1	I2	I3	I4	I5	I6	I7	I8	I9
I1	0	0.2	0	1	0	0	0	0	0
I2	1	0	0.2	0	0	0	0	0	0
I3	0	0	0	0.4	0	1	0.1	0	0
I4	1	0	0	0	1	0	0.2	0	0
I5	0	0	0	0	0	1	0.03	0	0
I6	0	0	1	0	1	0	0	0	0
I7	0	0	0	0	0.9	0	0	1	0
I8	0	0	0	0	0	0	1	0	1
I9	0	0	0	0	0	0	0	1	0

		A	A	A	B	B	B	C	C	C
		1	2	3	1	2	3	1	2	3
A	1	0	0	0	1	0	0	0	0	0
A	2	1	0	0	0	0	0	0	0	0
A	3	0	0	0	0	0	1	0	0	0
B	1	1	0	0	0	1	0	0	0	0
B	2	0	0	0	1	0	1	0	0	0
B	3	0	0	1	0	1	0	0	0	0
C	1	0	0	0	0	0	0	0	1	0
C	2	0	0	0	0	0	0	1	0	1
C	3	0	0	0	0	0	0	0	1	0

Fig. 1. Integration of the area approach in the IIM model: the two matrices represent the propagation of the failure in a single infrastructure (e.g. internal dependency from area A2 to area A1) given the general infrastructural interoperability (from infrastructure I2 to I1) described using the Leontief matrix

The risk quantification procedure, after having obtained the inoperability level for each infrastructure, develops through the evaluation, for all risk sources, of the accidents occurrence frequency and of the magnitude of casualties caused by such events: the consequent risk analysis proceeds as integration of 1) failure data (magnitude and frequency of a failure), 2) effects of propagation obtained via interoperability analysis, 3) information about physical position and 4) quantification of target's vulnerability (values and number of targets). For each target (k) in a given area (i) the risk value is given by the following equation (2):

$$R_{i,k} = c_i \cdot M_{i,k}(n, v) \cdot f_i \tag{2}$$

where area risk $R_{i,k}$ is derived from a given magnitude of failure effect $M_{i,k}$, related to the value (v) or number (n) of targets and the frequency (f) of failure for each single area of the map. A coefficient (c_i) represents the "activation" of effects in the area given the principal failure, in conformity with formula (1): the vector obtained by iterations is then used to calculate, area by area, the interoperability and the propagation of failure. The total amount of risk for each area ($R_{i,tot}$) is then (3):

$$R_{i,tot} = R_{i,p} \cdot w_p + R_{i,b} \cdot w_b + R_{i,c} \cdot w_c \tag{3}$$

equation used for integrating the different results obtained for each class of target (p = people, b = buildings and c = commercial activities). Transformation coefficients (w_p, w_b and w_c) are required in order to convert the magnitude of each target in an equivalent number of affected persons. The same methodological approach is used for analyzing interconnected infrastructures: a Leontief-like matrix (ref. Figure 1) is used to analyse infrastructural dependencies, as described in the following paragraph.

3 INTEGRATED APPROACH FOR AREA AND INTEROPERABILITY ANALYSIS

The proposed integrated approach is focused on: 1) the gathering and analysis of infrastructure data (e.g., types of infrastructure, related infrastructure services, types of possible failures of the components) to evaluate the interdependences (Leontief matrix); 2) the detailed description of the geographical area (e.g., extension, distribution, types and vulnerability of targets) served by the infrastructures and potentially affected by their disruptions. The main objective is to estimate the so-called "societal risk" (Post et al., 2006) in the considered area due to the failure and disruptions of critical infrastructure. A case study, related to the historical urban area of Cremona, a town located in Northern Italy, is given as example of application.

The study, in collaboration with Lombardy Region, its Technical Development Center (CESTEC) and Cremona Municipality, started from the spatial analysis (town maps based on GIS) and the "topographical" representation of each infrastructure (spatial distribution of the network and related components, analysis of nodes of the system). The first step is represented by the selection of the area (e.g. historical centre of the city) and then by the mapping of underground infrastructures and functional details (type of components, technical and physical characteristics, geographical distribution of the network, directly obtained from the utilities and other operators in form of reports and drawings). A second step of the analysis returns the “status of the surface” in terms of type and location of targets (via on-site inspections): people, buildings and commercial activities; in particular, each type of target must be: a) quantified in terms of vulnerability; b) related to the other types of targets; c) prioritised in terms of relative importance (e.g. persons vs. buildings). Tables 1 reports the synthesis of the quantification process and results.

Table 1. Prioritization, weights (from expert’s judgment) and quantification of damage for the vulnerability classes in the center of Cremona

Target	Priority index	Weight	Damage	Scale
Resident persons	10	37,0%	Death/injuries	# persons
Incoming persons	10	37,0%	Death/injuries	# persons
Buildings	3	11,1%	Struct. damage	0 - 100%
Comm. activities	2	7,4%	Loss of value	0 - 100%

3.1 Infrastructures and topological analysis: understand internal dependency propagation

Since the service continuity of a specific infrastructure depends on the correct functioning of its components and connections, a local failure can propagate its effects due to the internal dependencies established by the structure and topology of the infrastructure. Based on the IIM model it is possible to quantify the effect propagation (extension) of a failure given the matrix of internal dependencies of a selected networked infrastructure, in that rows and columns are sub-areas crossed by the infrastructure. For example a matrix is used to describe the topological and functional characteristics of the electric power distribution network in the considered urban area (Figure 2).

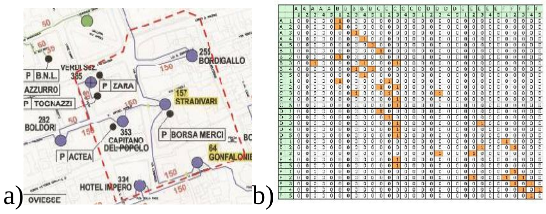


Fig. 2. a) Scheme of electric power distribution network (with low/medium voltage transformation cabins) in the urban area of Cremona and b) corresponding scheme (matrix) of internal dependencies

Indeed, each element of the matrix contains a value indicating the level (from 0 to 1) of the dependency associated to a couple of elementary areas (e.g. from area B3 to area A3) as a synthesis of dependencies related to the physical structure of the network (cables) and vulnerability in front of given component failure (cabin blackout); a level of interoperability equal to 1 is assumed for indicating the total inoperability of the connected lines in front of a cabin blackout.

3.2 Interoperability and geographical analysis: understand external dependencies

After having analyzed the propagation of a failure in a single infrastructure the next step demonstrates the fundamental capability of the method to take into account the geographical impact of the interconnected infrastructures and services. To this end a “generalized” Leontief-like matrix is used, where different infrastructures and relationships between them, the weights of the dependencies and the information regarding the presence of components in the specific area, are reported.

As described above the modeling of the problem is done by using a sub matrix containing either in rows and columns both infrastructures and areas (e.g. dependency from a given infrastructure in area A2 to another one in B2); while the interoperability between n infrastructures is represented by a general matrix containing 2^n sub-matrices.

For the sake of brevity only the interoperability analysis between electricity and district heating is presented, as shown in Figure 3. Please note that:

- the diagonal of the general matrix represents the internal dependency of each infrastructure (respectively electric and district heating supply);
- the zero matrix (in the upper right side) points out the independency of the electric supply from the district heating infrastructure;
- the lower left side of the matrix states the interoperability between the two services and the external propagation of the failure: from an electric failure to a loss of service in the heating distribution.

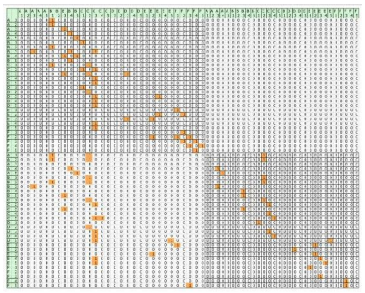


Fig. 3. External dependencies from the electric power infrastructure to district heating service. Note that the diagonal matrices represent the internal dependencies of each infrastructure

Clearly a sub-matrix represents the geographical extension of the interdependency between two infrastructures, and is particularly useful not only for a complete interdependency analysis but also to analyze the geographical propagation of damage and estimate its final extension. In the case study this kind of analysis revealed all the areas potentially affected by a loss of heating supply due to a single failure in the electric power network. We predicted the zones affected by a domino effect starting from a predetermined damage point (B3) where a failure occurs: a failure in the electric power network (black-out of an underground electric cabin) generates the blackout of the whole area, in terms of loss of electricity and district heating system.

4 RISK ANALYSIS FOR THE URBAN AREA OF CREMONA

The obtained area risk indices -from failure in area B3- (R_p, R_b, R_c and the linear combination $R_{i,tot}$), allows to map the vulnerability and resilience of the overall area of analysis in terms of combined effects of 1) direct inoperability of electricity 2) loss of district heating service for the population and commercial activities, as shown in Figure 4:

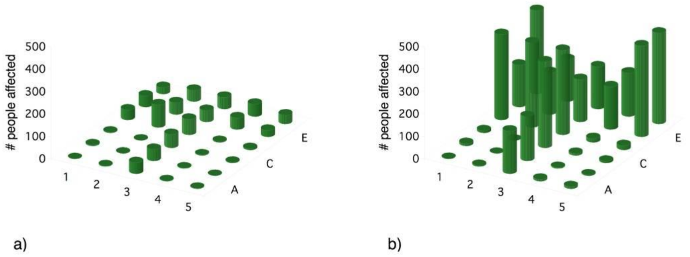


Fig. 4. Damages (expressed in equivalent affected persons) from a) loss of electricity supply b) loss of electricity and district heating supply given the failure in area B3

4.1 Results and analysis

Clearly the two set of risk mapping are very different and this is due to the fact that a) the second analysis has been done as integration of both services and effects, b) in the second case the effects of loss of heating service affects directly persons, that have an higher level of vulnerability (37%) respect to the commercial activities (7,4%), targets of electricity loss of service. Moreover, a mitigation plan, devoted to increase the resilience of most critical areas, can be defined considering not only the risk level of each type of failure in different areas but also the geographical information on damage propagation; indeed, referring to the case study, the major effects of the considered failure (starting from the upper zone of the map) are concentrated in the lower zone, corresponding to the areas with the higher number of residents, incoming persons and commercial activities. Finally, the same approach allows to analyze: a) the effects of multiple failures into the area for a single infrastructure; and b) the total effect of failures on the entire set of infrastructures given different classes of target or sum of them.

4.2 Risk Mitigation Plan and Infrastructure Resilience

As shown in the previous section, the consequences of a failure are not only the direct risk on the surface targets, but also the loss of services induced by the interoperability. Thus the total risk must take into account the possible effects that such a failure can have on other(s) infrastructure(s). For example, as a result of excavation for repairing a failure in the electricity network, other infrastructures located underground can be partially damaged inducing further failure phenomena.

As shown in Figure 5 the described analysis is able to specify all these dynamics: 1) the direct impact (hazard of electrical shock) for the persons, specified (in terms of area risk) with a circle area, and 2) the indirect effects on other infrastructures in each area (red zones). To limit indirect effects and thus to increase the resilience of the underground infrastructures, the preliminary analysis carried out in the case study suggested to put particular attention on the maintenance of the three low/medium voltage cabins “157”, “255” and “353”, sited in the centre of the area .

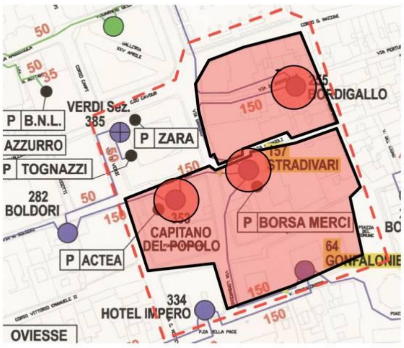


Fig. 5. Direct impact of the electrical hazard (circle) and related black out effects (area)

5 CONCLUSIONS

The presented methodology has focused on the comprehension and integration of the complex interdependencies between different critical infrastructures. The principal characteristic of the approach consists in the physical and geographical description of the interdependencies: in fact each infrastructure has been studied in terms of mutual damage capability given technical analysis of the failure modes. The propagation of a single or interrelated damage has been described using the interoperability approach integrated with a well-known area risk approach. Then a preliminary case study, based on technical data and maps, demonstrates the importance of this approach in terms of risk analysis, based on the combination of the direct and indirect effect of a potential damage, and resilience analysis. Future developments concern the better comprehension of the damage evolution in the infrastructures and the time-dependent risk evaluation. Finally an extension of the case study should be applied in an entire urban area.

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