A global approach to risk assessment of critical infrastructures

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We consider a holistic approach to risk analysis of complex Critical Infrastructures (CI) through a new generation Decision Support System (DSS) designed for the prediction of Crisis Scenarios induced by natural hazards and the evaluation of their impacts. The system relies on accurate, high resolution LAMs (Local Area Model) providing weather and other events forecasts. These results, used in conjunction with GIS (Geographic Information System) databases containing thematic information at regional scale, are used to evaluate impacts on population, buildings, and infrastructures. Resulting damages scenarios are then used in combination with CI specific simulators, to gain estimates of the reduction (or loss) in their functionality, also considering dependency effects. Implementation of such DSS is going to be accomplished in the framework of a large pan-European network, CIPRNET (Critical Infrastructures Preparedness and Resilience Network) recently started.

Keywords: risk analysis, forecast, natural hazards; preparedness

Subject classification codes:

Introduction

Critical Infrastructures Protection (CIP) and, in general, the enhancement of the preparedness of infrastructures operators to face crisis scenarios which may open due to natural hazards or deliberate malevolent actions is a major concern of modern countries. Nowadays, CI are often far from being "stand alone" systems whose control could be allotted to a no matter how complex "operation room", yet they compose an entangled "system of systems" where each CI provides and receives support from the others. Moreover, CI exhibit transnational extension and impacts: as such, their management should not be tackled "locally" but should involve analysis of data coming from far away areas, possibly from different countries. The latter situation has been stated in the EU Directive 2008/114/EC which, defining European Critical Infrastructures, clearly underlines this scenario and asks EU Member States to protect their own CI and share data with other EU countries for the protection of such transnational "system of systems". In such a complex context, the approach to risk analysis and protection of infrastructures cannot be tackled by isolating each CI from the others, in a sort of linearized approach but, in turn, engaging all of them in a holistic approach.

In a recent investigation devoted to the statistical identification of sources of failures of CI [1], it has been estimated that 2% of the total number of failures (including common mode failures) occurred over a period of 12 years in US and Canada, depends on natural causes and 1% on deliberate man-made attacks (the remaining causes of failures, not relevant to this work aims, are: software and hardware faults, human errors, overload, authorization violation, malicious logic faults). Other data [2] points to a larger fraction of damages produced by natural events. This pushes to improve methods for predicting events and their impacts, to be used for optimizing mitigation, healing and emergency strategies.

Therefore, it is of particular relevance to devote efforts for the realization of risk analysis tools based on holistic approaches which, starting from the prediction of the probability (in a given area and at a given time) of occurrence of natural disasters (e.g. flooding, earthquakes, lightning strikes, landslides, fires, etc.), are able to: a) infer the probability of occurrence of faults in CI elements, b) evaluate the impact that expected damages might have on a set of dependent CI and c) assess the consequences on the service levels provided to citizens. However such tools could also be used to model "synthetic" damage scenarios produced by other means (man attacks, common mode failures etc.) and could thus be used for analysis impacts due to "endogenous" causes.

This is, at large, the technological purposes motivating the new EU network initiative CIPRNET (Critical Infrastructures Preparedness Research Network) which aims at realizing activities for providing technological tools to improve methods for enhancing CI resilience and to set up new strategic initiatives to be proposed to national states.

The present work will mainly deal with the description of the first task. The CIPRNET consortium wishes, on the technological side, to implement a complete operational pipeline which could be designed, realized and tested in an operational mode, enabling a 24/7 supervision of the events which could hit CI elements and increase, the risk associated to their loss (or service reduction) beyond given thresholds.

Human population experienced a series of natural disasters such as hurricanes, tsunamis, earthquakes, floods, fires, landslides among others, that have, in several cases, overwhelmed the response and recovery capacities. Modern geospatial technologies (such as satellite imaging and Geographical Information Systems, GIS) make possible to implement ad hoc DSS, able to support various phases during the Disaster Management activities (e.g. preparation, response/mitigation, recovery and aftercare) of disastrous events but also to evaluate the consequences that these events may cause.

Modern approaches to emergency management and response involve efforts to reduce the vulnerability to hazards, to reduce the impact of disasters and to prepare for, responding to, and recovering from those that may occur [2]. Geospatial data and tools have the potential to contribute to all these emergency tasks [3]. Decision makers and responders, who know where disaster impacts are expected to be greatest, where critical assets are located or where infrastructure are likely been damaged, will be able to act more promptly and effectively, especially immediately after the initiating event [4].

The DSS inserted in the CIPRNET roadmap, has been conceived to connect static data (historical, current etc.) with real-time or near real-time data (e.g., from sensor networks) and simulation results through an 'Intelligent Software Architecture'. In this way, the DSS will deal with the problem of estimating the threats to which each element of CI is subjected by extreme events (e.g., extreme rainfalls, floods, landslides, earthquakes, etc.) and the impact that its loss could have on the Quality of Service (QoS) provided by the infrastructure it belongs to.

The DSS architecture consists in: 1) a geospatial database DB (CIPRNet DB in the following); 2) a local GIS application for analysing and modelling the hazardous event and their impacts on CI functioning, on population, environments and supporting emergency management; 3) a WebGIS interface for sharing the geo-localized information among the private and public stakeholders and emergency managers.

In the following sections, we will briefly describe the operational workflow which is intended to be realized and provide some information on specific points of the workflow which are related to state of the art improvements which CIPRNET wishes to achieve.

General scheme of the CIPRNET operational workflow

The core of the proposed architectural flow is represented by the so-called "DSS Risk Assessment Workflow". Figure 1 shows the different functional bricks (Bn) of this workflow:

- ***sensing the environment (B1)***
- ***events forecast and/or event detection (B2)***
- ***predicting damage scenarios (B3)***
- ***estimating impacts (B4)***
- ***decision support (B5)***

In Figure 1, bricks depicted in green are meant to correspond to "external" actions, granted by functional applications performed by "external" players (external partners, CI operators, external services etc.), which provide data and other resources to the DSS system. Blue bricks represent "internal" tasks performed by CIPRNET infrastructures. From the technical point of view, a system "orchestrator" controlling the input/output of data and actions' flow will grant internal and external tasks/interaction.

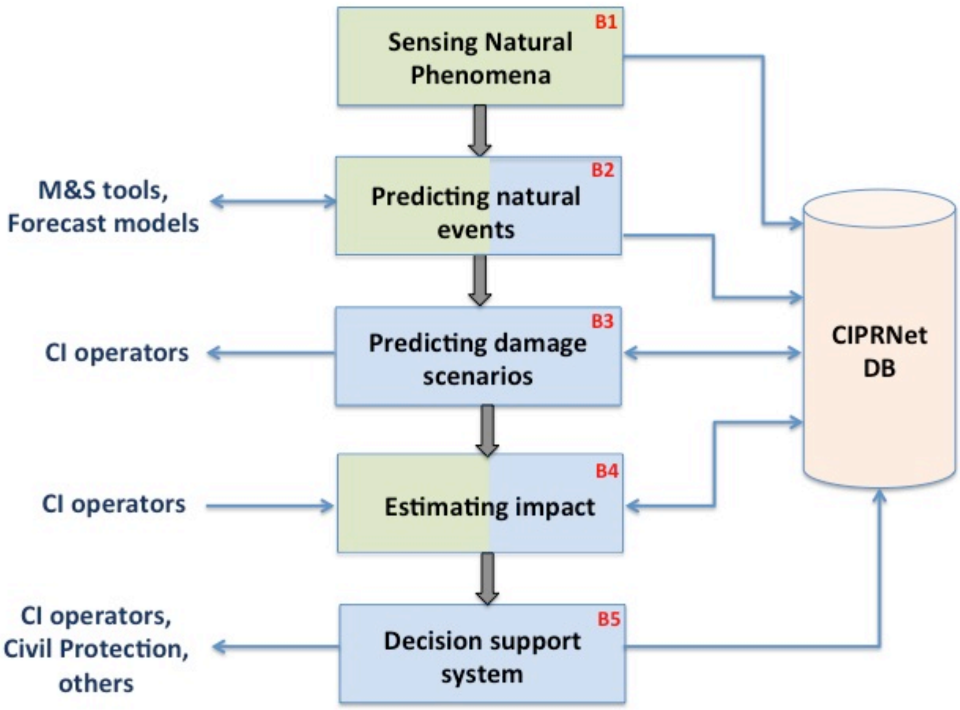


Figure 1. Different phases ("bricks") of the proposed DSS Risk Assessment Workflow

Data stored in the CIPRNet DB will belong to different pre-defined layers:

- Territorial layer
- Socio-economical layer
- Technological Infrastructure layer

- Historical events layer (e.g. earthquakes, landslides, rain precipitation records, etc.).
- Technical datasheet of CI elements

Data sources can be governmental repositories, infrastructure operators operative centres, monitoring sensor networks (e.g. weather forecast data or geo-seismic sensors networks) etc. The database will gather and store available historical data and will allow the development and the maintenance of historical series. CIPRNet DSS will also leverage on data from external repositories (e.g. by means of GIS WMS protocols/services).

In the following sections, each functional brick will be presented and its main functions explained.

B1: Sensing the environment

B1 can be considered as an external (green) phase as it represents the action of feeding the DSS DB with external (field) data. These will encompass geo-seismic data, weather data and, in general, "raw" data, which the system should be able to handle, use for its purposes and store into its DB. Typical data follow:

- data from seismic monitoring network to detect earthquakes (localization, magnitude);
- Data from meteorological network, air quality etc.;
- Data from *Nowcasting* radars (X- and C-band);
- Remote sensed images (SAR and/or multispectral satellite platforms).

B2: Events forecast and/or event detection

Event prediction is a first step toward the definition of crisis scenarios. On the bases of data incoming from B1, B2 will forecast natural phenomena at the appropriate (LAM) scale with indication of precipitation abundance, wind speed etc. All available data will be fused to provide the most accurate forecast of natural hazards within a specified temporal horizon. In particular, we define the Risk Assessment Forecast Interval (RAFI in the following), as the next temporal horizon (expressed in hours) of the risk assessment methodology. For the proposed configuration, the RAFI parameter would be set to 48 hours: this will mean that at t=0 the system will provide a forecast value for the next 48 hours. To provide a couple of examples, we can consider the following B2 workflows:

- meteorological data are used to forecast rain precipitation in a specific area. Such data can be used to input hydrological models of specific areas (whose data are stored within the DB) to forecast a flooding event.
- the detection of earthquakes primary shock could be propagated in a specific area to produce the expected local shake maps. The case of earthquakes is peculiar with respect to predictable hazards: it will be detected as an event occurred at t=0. From the triggering information on appropriate sensors network, B2 will propagates its physical parameters (with appropriate models) to produce the shake maps in the epicentre surrounding areas. The system should be able to detect if the area under observation will be affected by a PGA (Peak Ground Acceleration) larger than a fixed threshold that is related to the infrastructures vulnerability.

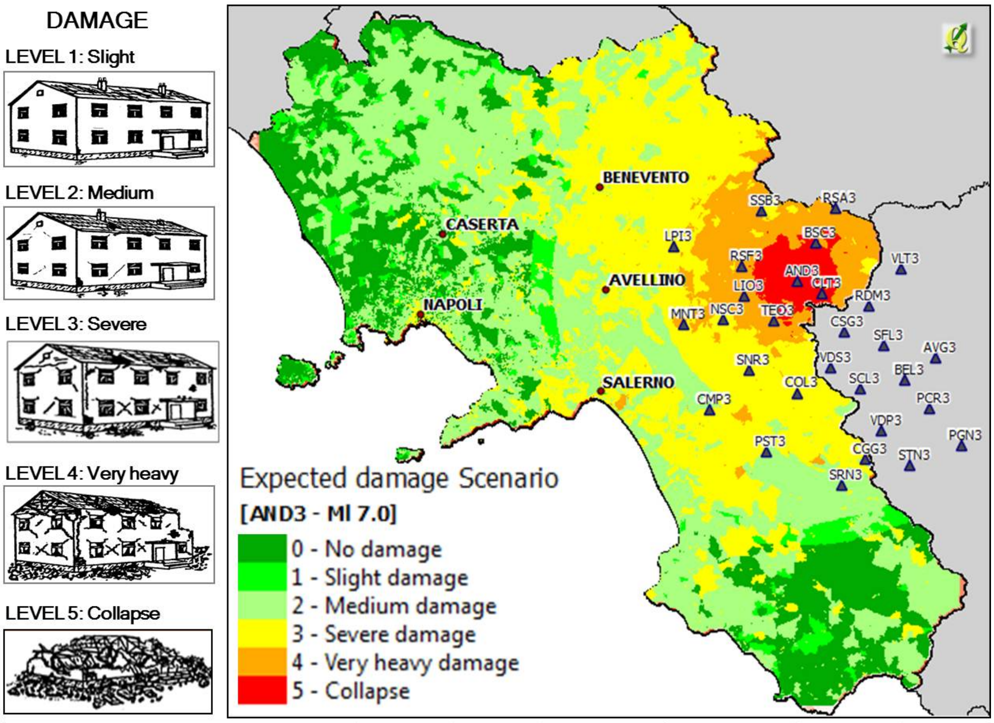
Thus, predicting and mapping the vulnerability of an area (or, more exactly, of the infrastructures there located) and assessing potential impacts of an event in that area will play a crucial role in the emergency management [5].

B3: Predicting damage scenario

Once the natural hazards are adequately characterized, the next step is the estimate of damages occurring to CI elements if hit by the predicted natural hazards. This will be provided in terms of the *Damage Probability* of each CI component in the specified RAFI time frame. This phase will involve the evaluation of the damage that different CI components are likely to suffer and that of their specific loss (or reduction) of functionality (expressed in terms of fraction of their normal operational efficiency). B3 will outcome a *Damages Scenario* describing the affected CI components and their damage extent. Detailed reports describing the *Damage Scenario* will be rapidly provided to the operators of the involved CI. Estimates will be performed by using both historical data and vulnerability assessment based on empirical functions. *Damage Probability* of different components can, indeed, depend on the specific hazards. For example, abundant rain precipitation could result in flooding and landslide hazards that will contribute in different ways to the final CI components Damage Probability. To evaluate the vulnerability of structures, a detailed inventory of the area of interest is needed and well-defined relationships between event types (earthquake, flood, etc.) and both structural and non-structural damage have to be identified. The vulnerability estimate allows measuring how the infrastructures are susceptible to suffer damage by a specific event. As a concrete example one may take the earthquakes [6], where buildings' inventory can be derived by institutional dataset (in Italy, for instance, ISTAT Census dataset granted by Italian National Institute of Statistics. http://www.istat.it/en/). Aggregated data related to built-up density, structural typology, age of construction, etc., derived by using GIS geo-processing and spatial analysis tools, can be used to assess and map the vulnerability (by a specific index) for each census section [7]. In the following section is reported an example concerning the evaluation of damage scenarios in case of seismic events.

Damage scenario after an earthquake

After the reception of an earthquake alert and the reconstructed magnitude and depth of the primary shock, B3 will elaborate, with its own geo-morphological data, the propagation of the shock wave up to the region under observation. This will produce the expected shake maps at ground level which, in turn, will be used as input to estimate the degree of damage of the buildings (whose main characteristics can be derived from specific dataset) and other infrastructures (roads, railways etc.). This information will be provided under the form of a damage map, such as that reported in fig.2 referring to a simulation of the damages produced by a (synthetic) earthquake in the Irpinia region (east of the highly-populated Naples area).



Levels of Damage	0	1	2	3	4	5
Factor of Damage (f_d)	0	0.01	0.1	0.35	0.75	1

Figure 2. Predicted scenario of buildings' damage after a large (synthetic) earthquake

occurring in the Irpinia (Southern Italy, east of Naples). A scale of false colours provides immediate visual prospect of damage extent. A standard range of damages from 0 to 5 is assigned by using the methods reported in [6].

Estimated damage level of different CI present in the area could be thus provided to CI operators (and to other actors as we will see in functional brick B5) within a few minutes from the event, much earlier than any inventory on the field. The proposed DSS will thus deploy all the information (geographic data, thematic maps and damage scenarios) on suitable Internet platforms that will allow regulated access through a specific WebGIS interface. This tool will also provide interactive query capabilities and integrate the GIS solutions with other technologies.

B4: Estimating impacts

This is the most complex task as it involves a number of different evaluations and will be performed by a tight collaboration between CIP experts and CI operators. For this reason, the brick is depicted in fig.1 as a "mixed" (green and blue) box. As far as its final output is concerned, it should provide impacts on both the Infrastructures (in terms of reduction or loss of functionality) and the corresponding human organizations or activities (citizens' health, goods delivery, land asset etc.).

Impact on CI. As described in B3, the *Damage Scenario* individuates the CI elements (on a single or multiple CI) whose damage probability will be above a given threshold. This information is rapidly provided to operators of the involved CI. In B4, starting from the predicted and transmitted functionality loss of their single elements, the asset owners will be asked to provide back information on the reduction (or the loss) of functionality of their *whole* infrastructures as a consequence of the element(s) fault. The CI crisis managers will generate the resulting prediction by using their own simulators, fed with data representing the effective state of their infrastructures at the time when the damage would occur. The DSS will thus receive back, from the different CI operators, the estimated impacts list. In the most favourable case, the DSS will be provided with *Quantitative CI Impact Evaluation* data (resulting from operator's infrastructures simulators). However, if for some reasons, it will not be possible to get such quantitative data from CI operators, the DSS will revert on *Qualitative CI Impact Evaluation* data computed using CIPRNet internal modelling and simulation capabilities. The DSS will then gather all the functional impacts on the different CIs that, in turn, will be supplied as input to a *multi-infrastructures simulator* (like e.g. I2Sim[8]), which will enable the DSS to provide a global assessment of the *consequences* of multiple impacts on the system of *dependent* infrastructures. I2Sim will be recursively called to perform "self-consistent" loops allowing the evaluation of the "equilibrium" state resulting from the synergic aggregation (i.e. taking into account feedback loops due to system's dependency which could undermine the single infrastructure resulting impact, as predicted by operators) of all dependent impacts reported from the different infrastructures.

Impact on society. After having estimated the impact scenario on CI, the DSS will evaluate the consequences on the different societal activities (economic and societal system), environment (whenever CI fault would imply environmental damage such as air or water pollution etc.), on life and welfare of all living beings. These consequences are typically assessed by crossing the resulting impact on the CI system with information layers of the DB (to extract quantitative information about, for instance, economical and "welfare" losses etc.). To this end, the proposed WebGIS interface, as integrated part of DSS, is able to support the risk assessment analyses and the emergency management tasks, by allowing the visualization and analysis of the geospatial data and thematic maps stored in the CIPRNet DB. Basic functionalities will be developed to specific purposes such as: description and characterization of the area of interest, vulnerability/risk maps, impact scenarios and their time evolution.

B5: Decision support

The DSS will then consolidate the final “crisis assessment” into a document delivered (in “quasi” real time) to all the players involved in the operations, from CI operators to Civil Protection, to Public Administration, in a way to allow them to have a *coherent* set of information on which they could properly elaborate coherent mitigation and healing strategies and, whenever the case, Emergency plans.

Conclusions

The proposed unifying picture derives from the awareness that the inclusion of a capability of predicting environmental threats and considering the environment as a propagator of perturbations are key ingredients for the effectiveness of coherent and reliable systems for risk assessment.

The proposed approach improves the effectiveness of disaster monitoring, management and awareness. Its advantage is that the system is open and additional data can be integrated as soon as new information is available. The result will be an interactive DSS, which is able to support public and private stakeholders to quickly evaluating consequences for CI, people and environment and to address - in the post-event phase - activities related to emergency management.

This holistic approach to risk analysis is intrinsically multi-disciplinary, as it involves the clustering of a number of expertises, from those related to CI to those of weather forecasting, geoscience, seismology etc. This approach will certainly foster in the future a new generation of risk assessment tools which will be more efficient and will enable an easier and more effective management of crises.

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