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Abstract

The SYNER-G project aims at developing a methodology to evaluate the vulnerability to earthquakes of a complex system of interconnected infrastructural systems of regional/urban extension. This report aims to summarize the developed methodology, which is based on smart simulation of an object-orientated model of the system to account for the uncertainties involved (in the hazard, as well as in the system) and to tackle the complexity of the interactions existing within each system between its components, and across the systems. The methodology integrates within the same framework the hazard, the physical vulnerability and the social consequences/impact. The strength of the object-orientated foundation of the model is that it can be easily expanded and developed step-wise, allowing for multiple choices for each intermediate model. This allows also the integration of previous research results and models within a larger simulation framework for distributed infrastructural systems. The developed methodology is implemented in the SYNER-G software toolbox.

Keywords: SYNER-G methodology; synthetic deliverable
Acknowledgments

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1 Introduction

This report presents, in a synthetic way, the general methodology developed within the SYNER-G project for the assessment of the seismic vulnerability of infrastructures. This chapter gives a brief introduction to the dimensions that have to be considered in a systemic study and on the spatial characterization of the components of the infrastructure. Chapter 2 presents a schematic and identified taxonomy of infrastructural systems. Chapter 3 synthesizes the general methodology presenting first the object-oriented approach that has been adopted in the project and then the infrastructure and the hazard model that have been implemented. Finally the uncertainties and the probabilistic evaluation of the performance of an infrastructure is presented. For more details the reader is referred to Deliverable 2.1 and Deliverable 8.7. This developed methodology is based on smart simulation of an object-oriented model of the system to account for the uncertainties involved (in the hazard, as well as in the system) and to tackle the complexity of the interactions existing within each system between its components, and across the systems. The methodology integrates within the same framework the hazard, the physical vulnerability and the social consequences/impact. The strength of the object-oriented foundation of the model is that it can be easily expanded and developed step-wise, allowing for multiple choices for each intermediate model. This allows also the integration of previous research results and models within a larger simulation framework for distributed infrastructural systems.

When the focus is on a systemic study, there are three main dimensions that have to be considered: time, space and stakeholders. The impact of the disaster caused by a natural hazard (which is an earthquake within SYNER-G) on a system evolves with time elapsed from the event and in space. Furthermore, different stakeholders may have different stakes and play different roles in dealing with the various phases of the disaster, and are correspondingly interested in the assessment of the impact in different ways. These dimensions of the systemic study are represented in Fig. 1.1. As far the time dimension is concerned, two aspects are of interest: the time-frame and the observation point-in-time. Typically, three frames are considered:

- **short-term**: in the aftermath of the event the damaged Infrastructure operates in a state of emergency;

- **mid-term**: the Infrastructure progressively returns to a new state of normal functionality;

- **long-term**: the Infrastructure is upgraded/retrofitted with available resources to mitigate the risk from the next event.

Correspondingly, the spatial extent of interest to the study of the Infrastructure response increases with time, initially (short-term) involving only the local impacted area, then, an increasingly wide area covering adjacent regions, up to the national scale in the economic recovery phase and long-term risk mitigation actions.
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Fig. 1.1 The three dimensions in an Infrastructure vulnerability study.

The position on the time axis of the observer with respect to the time-frame changes the goal of the systemic study:

- **before the time-frame**: the goal of the system analyst is forecasting the impact in order to set-up mitigation measures. It is important to underline how the information basis in this case can be considered as constant.
- **within the time-frame**: the goal of the system analyst is that of providing the managers with a real-time decision support system, which updates the Infrastructure state based on the continuously incoming flow of information.
- **after the time-frame**: the goal of the system analyst is to validate the models against occurred events.

Systemic studies of different nature most commonly address the following two phases:
- Emergency phase: short-term (a few days/weeks) at the urban/regional scale
- Economic recovery phase: medium to long-term, at the regional/national scale

The contribution of Engineering disciplines is obviously capital to the first phase. During the second phase their role becomes to some extent ancillary, due to the intervention of political and economic factors in the decision-making process.

The developed SYNER-G methodology focuses on the first phase only, with Emergency managers as the reference Stakeholders, and with the goal of forecasting before the event the expected impact for the purpose of planning and implementing risk mitigation measures.

The spatial characterization of the components (sub-systems) of the infrastructure has a direct relation with the approaches to be used for the definition of both the corresponding hazard and vulnerability. From a geometric point of view three categories can be identified:

- **Point-like components** (*Critical facilities*): single-site facilities whose importance for the functionality of the Infrastructure makes them critical, justifying a detailed description and analysis. Examples include hospitals, power-plants.
- **Line-like components** (*networks, lifelines*): distributed systems comprising a number of vulnerable point-like sub-systems in their vertices, and strongly characterized by their flow-transmission function. Examples include Electric networks with vulnerable power plants, sub-stations, etc, or road networks with vulnerable bridges.
- **Area-like components**: this is a special category specifically intended to model large populations of residential, office and commercial buildings, that cannot be treated individually. These buildings make up the largest proportion of the built...
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environment and generally give the predominant contribution to the total direct loss due to physical damage.

The approach for a vulnerability study of the area-like components is not homogeneous with that of the point-like and line-like sub-systems. The area-like components, for the purpose of a systemic study within SYNER-G, have been modelled with geo-cells characterized in terms of physical (distribution of buildings amongst standardized typologies with associated fragilities) and socio-economic (population, income, etc) parameters. In Fig. 1.2 the different categories of components/sub-systems of the Infrastructure are shown and the area-like component is represented by a census tract.

Fig. 1.2 Illustration of the different categories of components/sub-systems of the Infrastructure.
2 Taxonomy of the infrastructure

In order to tackle the complexity of devising a model of the entire infrastructure the first task undertaken within the project was the identification and description of a set of systems, sub-systems and components to focus on. This has resulted in what is called the SYNER-G taxonomy and a more detailed version of this taxonomy can be found in the deliverable D2.1, Appendix B, with description of each component type. All considered systems and their components have been assigned unique tags used consistently throughout the project. This taxonomy has been the guidance for the work carried out within Work Packages (WP) 3 and 5, within which, for each component, typology fragility models have been revised and/or developed, with a focus on European distinctive features, and systems have been modelled, respectively.

For the purpose of summarising the taxonomy, in the following table all the systems, components and their sub-components considered in the infrastructure are reported with their tags.

Table 2.1: Infrastructure taxonomy.

<table>
<thead>
<tr>
<th>System</th>
<th>Component (and sub-components)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BDG: building aggregates</td>
<td></td>
</tr>
<tr>
<td>2. HCS: health-care system</td>
<td>HCS01: organisational</td>
</tr>
<tr>
<td></td>
<td>HCS02: human</td>
</tr>
<tr>
<td></td>
<td>HCS03: physical</td>
</tr>
<tr>
<td></td>
<td>- HCS03-1: structural elements (of the buildings within the complex/facility)</td>
</tr>
<tr>
<td></td>
<td>- HCS03-2: non-structural elements/architectural</td>
</tr>
<tr>
<td></td>
<td>- HCS03-3: non-structural elements/basic installations/medical gases</td>
</tr>
<tr>
<td></td>
<td>- HCS03-4: non-structural elements/ basic installations/power system</td>
</tr>
<tr>
<td></td>
<td>- HCS03-5: non-structural elements/ basic installations/water system</td>
</tr>
<tr>
<td></td>
<td>- HCS03-6: non-structural elements/ basic installations/conveying system</td>
</tr>
<tr>
<td></td>
<td>- HCS03-7: non-structural elements/content-equipment</td>
</tr>
<tr>
<td>3. HBR: harbour</td>
<td>HBR01: waterfront components (wharves, breakwaters, etc.)</td>
</tr>
<tr>
<td></td>
<td>HBR02: earthen embankments (hydraulic fills and native soil material)</td>
</tr>
</tbody>
</table>
## Taxonomy of the infrastructure

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBR03</td>
<td>Cargo handling and storage components (cranes, tanks, etc)</td>
</tr>
<tr>
<td>HBR04</td>
<td>Buildings (sheds, warehouse, offices, etc)</td>
</tr>
<tr>
<td>HBR05</td>
<td>Liquid fuel system (components as per the OIL system)</td>
</tr>
</tbody>
</table>

### 4. RDN: road network
- RDN01: bridge
- RDN02: tunnel
- RDN03: embankment (road on)
- RDN04: trench (road in a)
- RDN05: Unstable slope (road on, or running along)

### 5. RWN: railway network
- RWN01: bridge, same as per RDN
- RWN02: tunnel, same as per RDN
- RWN03: embankment (road on), same as per RDN
- RWN04: trench (road in a), same as per RDN
- RWN05: unstable slope (road on, or running along), same as per RDN
- RWN06: SCADA system
- RWN07: station

### 6. WSS: water-supply network
- WSS01: water Source (Springs, shallow or deep wells, rivers, natural lakes, and impounding reservoirs)
- WSS02: water treatment plant
- WSS03: pumping station
- WSS04: storage tank
- WSS05: pipe
- WSS06: tunnel
- WSS07: canal
- WSS08: SCADA system

### 7. WWN: waste-water network
- WWN01: waste-water treatment plant
- WWN02: pumping station
- WWN03: same as per WSS
- WWN04: same as per WSS

### 8. FFS: fire-fighting system
- FFS01: fire-fighters station
- FFS02: pumping station
- FFS03: storage tank
- FFS04: fire-hydrant
## Taxonomy of the infrastructure

<table>
<thead>
<tr>
<th>Infrastructure Type</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FFS05: pipe</strong></td>
<td></td>
</tr>
</tbody>
</table>
| **9. EPN: electric power network** | EPN01: power generation facility (Nuclear, hydro-electric, thermo-electric, geothermal, solar etc.)  
EPN02: sub-station (distribution, transformation-distribution)  
EPN03: maintenance and technical support facilities  
EPN04: line  
EPN05: SCADA system |
| **10. GAS: natural gas system** | GAS01: production and gathering facility (Onshore, Offshore)  
GAS02: treatment plant  
GAS03: storage tank farm  
GAS04: station (Compression, Metering, Compression/metering, Regulator/metering)  
GAS05: regasifier  
GAS06: liquifier  
GAS07: pipe  
GAS08: SCADA |
| **11. OIL: oil system** | OIL01: production and gathering facility (Onshore, Offshore)  
OIL02: refinery  
OIL03: storage tank farm  
OIL04: pumping Station  
OIL05: pipe  
OIL06: SCADA |
The Syner-G Methodology

The goal of the general methodology developed within the SYNER-G project is to assess the seismic vulnerability of an infrastructure of urban/regional extension, accounting for inter- and intra-dependencies among infrastructural components, as well as for the uncertainties characterizing the problem. The goal has been achieved setting up a model of the infrastructure and of the hazard acting upon it, and then enhancing it with the introduction of the uncertainty and of the analysis methods that can evaluate the system performance accounting for such uncertainty.

The infrastructure model actually consists of two sets of models: the first set consists of the physical models of the systems making up the infrastructure. These models take as an input the hazards and provide as an output the state of physical/functional damage of the infrastructure. The second set of models consists of the socio-economic models that take among their input the output of the physical models and provide the socio-economic consequences of the event. The SYNER-G methodology integrates these models in a unified analysis procedure. In its final form the entire procedure is based on a sequence of three models: a) seismic hazard model, b) components’ physical vulnerability model, and c) system (functional and socio-economic) model.

For illustration purposes, with reference to the two socio-economic models identified and studied within Work Package 4 (the SHELTER and HEALTH-CARE models), Fig. 3.1 shows in qualitative terms the integrated procedure that leads from the evaluation of the hazard to that of the demands on the shelter and health-care system in terms of Displaced Population and Casualties, down to the assessment of social indexes like the Health Impact and the Shelter Needs. For more details the reader is referred to Deliverable 8.7.

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1 Within the SYNER-G project physical models have been developed in WP3 and WP5, while socio-economic models were developed in WP4.
Fig. 3.1 Integrated evaluation of physical and socio-economic performance indicators.

The conceptual sketch in Fig. 3.1 can be practically implemented by developing:

- A model for the spatially distributed seismic hazard
- A physical model of the Infrastructure
- Socio-economic models

Development of the hazard model has the goal of providing a tool for: a) sampling events in terms of location (epicentre) and possibly extension, magnitude and faulting style according to the seismicity of the study region b) predicting maps of seismic intensities at the sites of the vulnerable components in the infrastructure. These maps, conditional on M, epicentre, etc. should correctly describe the variability and spatial correlation of intensities at different sites. Further, when more vulnerable components exist at the same location and are sensitive to different intensities (e.g. acceleration and displacement), the model should predict intensities that are consistent at the same site.

Development of the physical model starts from the SYNER-G Taxonomy presented in the previous chapter and requires: a) for each system within the Taxonomy, a description of the
functioning of the system under both undisturbed and disturbed conditions (i.e. in the damaged state following an earthquake); b) a model for the physical and functional (seismic) damageability of each component within each system; c) identification of all dependencies between the systems; d) definition of adequate performance indicators for components and systems, and the infrastructure as a whole.

Development of the socio-economic model starts with an interface to outputs from the physical model in each of the four domains of SYNER-G (i.e., buildings, transportation systems, utility systems and critical facilities). Thus, four main performance indicators - Building Usability, Transportation Accessibility, Utility Functionality and Healthcare Treatment Capacity – are used to determine both direct and indirect impacts on society. Direct social losses are computed in terms of casualties and displaced populations. Indirect social losses are considered in two models – Shelter Needs and Health Impact – which employ the multi-criteria decision analysis (MCDA) theory for combining performance indicators from the physical and social vulnerability models.

In order to tackle the complexity of the described problem the object-oriented paradigm (OOP) has been adopted. In abstract terms, within such a paradigm, the problem is described as a set of objects, characterized in terms of attributes and methods, interacting with each other (see Section 3.1). Objects are instances (concrete realizations) of classes (abstract models, or templates for all objects with the same set of properties and methods).

### 3.1 OBJECT-ORIENTED APPROACH

As anticipated, an important choice in the development of the SYNER-G methodology has been to adopt the paradigm of object-oriented modelling. Object-oriented technology is built on a sound engineering foundation, whose elements are collectively called the object model of development or, simply, the object model, which is the conceptual framework for all things object-oriented. The object model encompasses the seven principles or elements of abstraction, encapsulation, modularity, hierarchy, typing, concurrency, and persistence. By themselves, none of these principles are new. What is important about the object model is that these elements are brought together in a synergistic way.

Having a well-defined and expressive notation is important to the process of software development, and more generally to the design of any model. For this reason, the Unified Modelling Language (UML) which is the primary modelling language used to analyze, specify, and design software systems, has been chosen. The UML has numerous types of diagrams, each providing a certain view of your system. One must understand both the structure and the function of the objects involved. One must understand the taxonomic structure of the class objects, the inheritance mechanisms used, the individual behaviours of objects, and the dynamic behaviour of the system as a whole. Amongst various available types of diagrams only two are used within this methodology: the class and the object diagrams.

A class diagram is used to show the existence of classes and their relationships in the logical view of a system. A single class diagram represents a view of the class structure of a system. The two essential elements of a class diagram are classes and their basic relationships. The class icon (used to represent a class in a class diagram) consists of three compartments, with the first occupied by the class name, the second by the properties (or
attributes), and the third by the methods (or functions/operations). A name is required for each class and must be unique to its enclosing namespace. Then it is worth noting that there are also abstract classes for which no instances may be created. Classes rarely stand alone. They collaborate with other classes in a variety of ways. The essential connections among classes include association, generalization, aggregation, and composition. Fig. 3.2 shows, for instance, the class diagram for the Hazard class. This class is the composition of two abstract classes: man-made and natural hazards. The class Natural contains environmental hazards such as seismic, volcano eruption, floods, etc. The seismic hazard, in turn, is modelled as the composition of three classes: one class for seismo-genetic sources, one for events and the third one for the local intensity at each site. Objects from the SeismicSource class are, as the name suggests, sources that can generate earthquakes. The class SeismicEvent is the class from which earthquakes in terms of localization and magnitude are instantiated. The passage from macro-seismic parameters to intensity values at each site of interest is performed by objects instantiated from the third class LocalIntensity.

![Class diagram for the Hazard class](image)

**Fig. 3.2 Class diagram for the Hazard class (the grey hatch, as indicated, denotes classes that have been included at the conceptual level but have not yet been implemented in the software)**

Fig. 3.3 shows another example of class diagram for WSS and EPN classes. Both the WSS and EPN classes are composition of node and link classes. For instance, for the water-supply system, links can either be pipes or tunnels, while nodes can be end-user demand nodes, water sources or pumping stations. As far as the electric-power network is concerned, links can be either overhead or buried lines, and there three node types: end-user demand nodes (load bus), electric power sources (generator) and a balance node, called the SlackBus, which is usually chosen as one of the power sources and is used as a mathematical expedient to solve the nonlinear alternate current (AC) equations (it provides the balance of flows during iterations in the solution). Load buses can be either distribution (D) or transformation/distribution sub-stations (TD). The two networks are shown in the same
figure to highlight the association between the pumping station class in the WSS and the
distribution and transformation/distribution classes in the EPN.

Fig. 3.3 Class diagram for the WSS and EPN classes (the grey hatch denotes classes
included at the conceptual level but not yet implemented in the software)

While classes are useful to represent all the systems with their high-level relationships, the
actual models on which the vulnerability analysis is carried out are not made of them, but,
rather, they are collection of objects. To better understand the difference between class and
object Error! Reference source not found. shows a sample WSS with the corresponding
set of objects. For example, the elementary WSS has two sources, a tank and a well (with
the associated pump), four demand nodes (two end-users with non-zero demands, and two
junctions, which are modelled as demand nodes with zero assigned demand) and a number
of connecting elements (five pipe segments and a tunnel). Correspondingly, there are five
objects (pipe1 to pipe5) of the class Pipe, one object tunnel of class Tunnel, etc.
3.2 INFRASTRUCTURE MODEL

The infrastructure model provides details on the modelling of the physical behaviour of a sub-set of the system from Syner-G taxonomy such as buildings and utilities. It has to be said that a central role is played by the area-like system made up of all residential/commercial/industrial buildings and in general of buildings that are not included among critical facilities. These buildings are where people live, work and consume goods and services. For this reason this system is the source of demands on all other systems (e.g. electric power and water supply demands, but also casualties to be transported through the road network to health-care facilities, displaced households seeking public shelter, etc.). Further, in terms of economic loss estimation, the largest proportion of direct loss due to physical damage and a considerable one of the indirect (e.g. business interruption) come from damage to these buildings.

Interaction within and between systems can be classified as Physical, Cyber, Geographic, Logical, Societal, Policy-related. Not all of them have been modelled within the methodology. Geographic interactions (physical proximity) are modelled in the seismic case by correctly incorporating within the seismic hazard model the statistical dependence structure between intensities at the same or close sites. Societal interactions are accounted for, e.g. in passing from a potential number of shelter-seeking population to the actual figure, incorporating factors such as anxiety, neighbourhood effects, income, etc.

Table 3.1 reports the interdependencies between some of the systems in the Taxonomy: the i-th row presents the influences of the i-th system on the other systems, while the j-th column collects the influences from other systems on the j-th system. The letter codes stand for: Physical (P), Demand (D) and Geographical (G) interactions. Numbers refer to the following descriptions of the interdependency type:
1. Fires in buildings can be triggered by earthquake induced damage thus raising the water-supply demand on the WSS (when this is not independent of the FFS);

2. In a urban setting, structural damage to buildings produces debris that can cause road blockages;

3. Structural and non-structural damage to buildings may result in casualties that need to be treated in a health-care facility and hence determine the demand on this system;

4. Damage to the EPN can lower the service level in the struck area, possibly below tolerance thresholds thus leading to population displacement and demand on the Shelter model;

5. Damage to the EPN can prevent functioning of pumping stations in the WSS;

6. Damage to the EPN can prevent functioning of re-gasification and regulation/metering stations in the GAS system;

7. Damage to the EPN can prevent functioning of stations in the OIL system;

8. Damage to the EPN can prevent functioning of critical components in the HBR system;

9. Damage to the EPN can prevent power to be fed to the health-care facilities hindering emergency response in case a joint failure of backup power sources occur.

10. Damage to the WSS can lower the service level in the struck area, possibly below tolerance thresholds thus leading to population displacement and demand on the Shelter model;

11. Damage to the WSS can prevent water to be delivered to the health-care facilities hindering emergency response over time in case backup reservoirs are depleted;

12. Damage to the GAS system lower the service level in the struck area, possibly below tolerance thresholds, especially in adverse weather conditions, thus leading to population displacement and demand on the Shelter model;

13. Damage to the GAS system can stop production in generators within the EPN inducing power shortages;

14. Damage to the GAS system can prevent natural gas to be fed to the health-care facilities hindering emergency response in case backup power sources depend on gas fuel.

15. Damage to the OIL system can stop production in generators within the EPN inducing power shortages;

16. Damage to the transportation network can block access to damaged buildings hindering emergency response;

17. Damage to the transportation network can block access to the HBR preventing goods to be dispatched and causing large economic loss;

18. Damage to the transportation network can block access to health-care facilities hindering emergency response;
19. Demand for transportation (which concur to the determination of the origin-destination matrix that drives traffic flows) of goods is generated in HBR (HBR is an origin).

20. Demand for transportation is generated in HCS (as a destination).

### Table 3.1 Interdependencies for sample system from the Taxonomy.

<table>
<thead>
<tr>
<th></th>
<th>BDG</th>
<th>EPN</th>
<th>WSS</th>
<th>GAS</th>
<th>OIL</th>
<th>RDN</th>
<th>HBR</th>
<th>HCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDG</td>
<td>D</td>
<td>D1</td>
<td>D</td>
<td>D</td>
<td>D2</td>
<td>D3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPN</td>
<td>P4</td>
<td>P5</td>
<td>P6</td>
<td>P7</td>
<td>P8</td>
<td>P9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSS</td>
<td>P10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P11</td>
<td></td>
</tr>
<tr>
<td>GAS</td>
<td>P12</td>
<td>P13</td>
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<td></td>
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<td></td>
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<tr>
<td>OIL</td>
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<td>P15</td>
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<tr>
<td>RDN</td>
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<td>HBR</td>
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<td>D20</td>
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</table>

The evaluation of the above interactions requires establishing a sequence of actions and messages between the objects making up the model. This sequence establishes an order in the evaluation of states of the objects, something that is described within UML with a so-called state diagram. Fig. 3.5 presents such a diagram. In any given overall system-of-systems evaluation, an initialization phase is performed first, with the BDG object setting up the region discretization into cells and passing their centroids to the other systems, which in turn compile a list of tributary cells for each of their demand node and assign this demand node as a reference node to the cells. Demand for goods and services is then evaluated and an analysis of all systems in the pre-earthquake undisturbed conditions is carried out. Then, for all considered events, generation of shake field (local intensities at all relevant locations, i.e. the systems’ components sites and cell centroids) is followed by evaluation of: 1) the EPN; 2) all other utilities, with direct damage and possible power losses from the EPN; 3) the BDG, with direct damage and utility loss; 4) the RDN, with demand from the BDG and closures due to direct damage to its elements as well as from road blockages; 5) the HCS with demand from the BDG system, service level from all utilities and accessibility from the RDN.
Fig. 3.5 State diagram to model the inter-dependencies: sequence in the evaluation of states of the objects and messages (quantities) transmitted between objects.

To preserve generality of the developed methodology it is paramount to devise a scheme which can accommodate information from the very detailed to the less accurate. In many practical applications there will not be enough data to adopt a modelling approach whereby all physical components are characterized and their functional links are described deterministically.

A distinction is thus made between:
o **Deterministic (hard) links**: direct physical/functional link between components that allow for deterministic evaluation of a system state from a known components' states vector. This is the case, e.g. when one knows the exact topology of an electric power network with enough details on the lines and loads that the system behaviour can be modelled through the governing power flow equations.

o **Non-deterministic (soft) links**: links of “statistical” nature, which describe the probability of a given system state, given the state of its components, or of another system. This links are an additional source of uncertainty that needs to be accounted for in the vulnerability estimation and one that ideally should be removed by improving on the data gathering phase. A typical example of a situation in which such a link is unavoidable, since the required resolution is not compatible with a realistic study, is that of road blockage due to debris.

The goal of the SYNER-G methodology is to assess the performance of the Infrastructure and of all its systems and components, when subjected to a seismic hazard. The quantitative measure of this performance is given by Performance Indicators (PIs), that express numerically either the comparison of a demand with a capacity quantity, or the consequence of a mitigation action, or the assembled consequences of all damages (the “impact”). Performance Indicators can be categorized, according to the level within the hierarchy of the infrastructure to which they refer, into component-level PIs, system-level PIs and system of systems or Infrastructure-level PIs.

### 3.3 SEISMIC HAZARD MODEL

The seismic vulnerability assessment of an infrastructure of regional extension requires fragility models for a large number of different components. These fragility models take an intensity measure, scalar or vector, and provide the probability of each damage state. In general multiple different components may share the same site. Thus, in order to assess the damage state of the infrastructure for any given event, it is necessary to predict a vector of IMs at all sites where one or more vulnerable components are present. This is the purpose of the seismic hazard model. The vector $s = \{ s_1, \ldots, s_n \}$ of length $m = \sum m_i$, where $s_i$ is the vector of length $m_i$ of seismic IMs at the $i$-th site, exhibits a variable degree of statistical dependence between its components, decaying with the distance between the sites, and usually larger between the components within each $s_i$ (zero distance). The hazard model provides tools to sampling events in terms of location (epicentre) and possibly extension, magnitude and faulting style according to the seismicity of the study region and tools to predicting maps of seismic intensities at the sites of the vulnerable components in the infrastructure. These maps, conditional on $M$, epicentre, etc. should correctly describe the variability and spatial correlation of intensities at different sites.

Moreover, in modelling the seismic risk to lifeline systems, the consideration of hazard from permanent deformation of the ground (PGD$D$) is paramount. For pipelines and similar systems with linear elements, fragility models are generally given in terms of PGD$D$, as they are most vulnerable to the permanent displacement of the ground rather than transient shaking. For application within SYNER-G, four primary causes of permanent ground
displacement are considered: liquefaction-induced lateral spread, liquefaction-induced settlement, slope displacement and coseismic fault rupture.

3.4 PROBABILISTIC ANALYSIS

The uncertainties entering the regional seismic vulnerability analysis are summarized below:

- Seismic activity of the seismo-genetic sources/faults (modelled through magnitude-recurrence laws and explained in report D2.13);
- Local seismic intensities at the sites (modelled through ground-motion prediction equations, spatial correlation models, cross-IM correlation models and site amplification models, and explained in report D2.13);
- Physical damageability of the components of the infrastructure (modelled by fragility models, e.g. explained in all reports from WP3);
- Uncertainty in the functional consequences at component and/or system level of the physical damage at the component level;
- Uncertainty in the socio-economic consequences of physical damage (non-structural components fragility models, probabilistic cost models, etc, reports from WP4);
- Epistemic uncertainty in all the above models.

The goal of the analysis is to evaluate probabilities or mean annual rates of events E defined in terms of performance-indicators of the types of infrastructure. This requires the joint probability model (distribution) of all the above uncertainties, denoted by \( f(x) \), where \( x \) is the vector that collects all random variables in the problem. The latter variables form a sequence of cause and effect and this sequence can be represented graphically in the form of a directed acyclic graph, which illustrates the flow from the rupturing fault/source, to event location and magnitude, the local intensities, the components’ state of physical damage, the functional consequences at system-level and finally the value of the performance indicators at the highest, Infrastructure, level. In Deliverable 8.7 the directed acyclic graph is explained in detail. Additional uncertainty in the results of the analysis comes from the epistemic uncertainty on the models and it can be considered by setting up a logic tree of model alternatives. Finally also the soft links can be included as additional random terms that enter in the relation between the physical damage state D and the performance PI. Notwithstanding this the SYNER-G software toolbox written to illustrate the methodology in its current stage of development does not account for the epistemic uncertainties in the models, or for the soft links. Moreover it has to be noted that the uncertainty related to the socio-economic portion of the integrated model is not represented, nor included yet.
Fig. 3.6 The sequence of models with associated input and output quantities.

Fig. 3.6 summarizes in very general terms what are the inputs and outputs exchanged by the three models for hazard, physical vulnerability and systemic consequences. Probabilistic evaluation of the performance of the infrastructure can be carried out with different methods (for instance, simulation methods or non-simulation methods). Simulation methods have been adopted and implemented within the SYNER-G software toolbox due to the fact that simulation is a robust way to explore the behaviour of systems of any complexity. Pragmatically, with the current state of knowledge in mind, the option adopted within the SYNER-G project to deal with the uncertainty is to resort to simulation methods and to reduce the required number of system evaluations by using advanced variance reduction techniques in order to arrive at probability estimates of the performances of interest.

The developed methodology is implemented in the SYNER-G software toolbox. It is coded in Matlab and the user interface is based on the software MAEVIZ which is a seismic risk assessment software developed by the Mid-America Earthquake (MAE) Center and the National Center for Supercomputing Applications (NCSA). The software toolbox will be available for download from the Syner-G website (http://www.vce.at/SYNER-G/) at the end of the project.
References


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