# PROJECT INFORMATION

<table>
<thead>
<tr>
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<th>Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain</th>
</tr>
</thead>
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<td>SYNER-G</td>
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# DELIVERABLE INFORMATION

<table>
<thead>
<tr>
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Abstract

This deliverable aims to specify the general methodology developed in WP2 for the “building system”. It gathers outcomes from WP2, WP3 and WP4 related to buildings and building aggregates and proposes a detailed methodology for this system.

In Section 1, the specificities of the buildings system are detailed, including the possible interactions with other systems and the performance indicators used. Section 2 focuses on the modelling of built areas within the SYNER-G methodology: following the object-oriented framework, all attributes and methods inherent to the buildings system are detailed in terms of input and output variables and algorithms used. Finally, in Section 3, the issue of probabilistic road blockages due to building collapse is tackled, and several approaches are proposed, depending on the type of data available for the study.

Keywords: Systemic vulnerability specification, buildings, road blockage
Acknowledgments

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1 General framework

1.1 INTRODUCTION

Whereas city-scale vulnerability assessment and seismic scenarios have recently become a practice with validated and detailed procedures, this type of analysis constitutes a key step in the SYNER-G methodological framework. Buildings and building aggregates play indeed an important role in the vulnerability of systems: collapsed buildings in urban areas may for instance induce the blockage of road segments downtown and prevent the transportation of emergency vehicles, while the number of casualties will greatly influence the performance of health-care systems. In addition, vital services related to civil protection, functionality of lifelines (e.g. control houses) and transportation infrastructures (e.g. terminal stations) as well as emergency facilities (e.g. fire fighting or health) are housed in buildings or building aggregates, commonly classified as “strategic buildings”. On the opposite, a thorough analysis of the inhabitability of a built area needs to go beyond the mere physical vulnerability assessment. Features such as a satisfying supply (depending on the demand generated by the built area) in basic utilities (water, electric power, gas, etc...) should also be considered. Furthermore, the buildings’ main function is to shelter population, and thus, they are the first elements to be taken into account in the socio-economic models, in order to evaluate societal impacts of a disaster (e.g. shelter model or health-care model). As a result, it is proposed in the SYNER-G framework to account for physical, functional and socio-economic vulnerability and loss assessment in one integrated and coherent methodology.

This deliverable aims at summarizing the results of the others work-packages (WP2, WP3 and WP4) in order to specify the general methodology to the building system and propose the framework for the implementation of different modules related to the vulnerability of buildings in the SYNER-G software.

1.2 COMPONENTS OF THE SYSTEM

Even if buildings are often individually described, accounting for their specific characteristics as presented in SYNER-G typology deliverable (D2.2 – Definition of system components and the formulation of system functions to evaluate the performance of buildings and building aggregates), vulnerability assessment and potential damage estimations are usually performed at larger scale. In the SYNER-G methodology, buildings and building aggregates are considered as area-type objects and they are represented by abstract cell elements (e.g. the meshing of a previously defined grid). This ‘raster’ approach allows indeed integrating data of various type and geographical scale, while still maintaining a satisfying level of spatial coherence: this solution has been deliberately chosen over the ‘vector’ approach, which relies on the creation of new areas from the intersection of all polygonal areas of the various datasets (see D2.1 – General methodology for systemic seismic vulnerability assessment).

The methodological framework developed within the SYNER-G project aims at integrating physical, functional and socio-economic vulnerabilities into a unified Buildings system. Thus, several sources of data need to be considered:
Building Census: this term encloses all information relative to the physical vulnerability of buildings. Whether it is the result of a field sampling of buildings or the analysis of various census datasets, the data is usually aggregated in polygonal areas at the scale of a building block or a small neighborhood. The attributes given by this Building Census data are for instance the number of buildings within each polygon, the percentage of each typology, or even the average height or built-up area (optional) (see also D2.11 - Methods for collecting, archiving and processing data on the typical European elements at risk within systems).

European Urban Audit: this database (Eurostat: http://epp.eurostat.ec.europa.eu) is available at sub-city district level for all major European cities. Many available attributes (demographics, unemployment rate, revenue level, etc…) are very useful to feed the shelter model or health-care model developed within Work Package 4 (Socio-economic vulnerability and losses). The most crucial information used here is the population living within each sub-city district, as it is required to compute the number of potential casualties.

Land Use Plan: this dataset defines which zones of the studied city or region are occupied by Green, Residential, Commercial or Industrial areas. This information can usually be extracted from a city's zonation regulation and it can then be used to define occupancy coefficients (depending on the time of the day, for instance), in order to adjust the number of people occupying a given type of buildings.

As a result, each cell of the Buildings system contains the projected attributes from these 3 sources of data. The global indicators, such as total number of collapsed buildings or casualties, can then be aggregated at the region level, by performing a summation over all cells.

1.2.1 Connections with other systems taken into account

Buildings and Building aggregates require inputs from other systems to be able to ensure their primary function, i.e. to be habitable. In the SYNER-G methodology, only the main dependencies have been taken into account (solid arrows in Figure 1-1).

The necessity for buildings to be connected to utility services in order to be habitable depends on their physical integrity and on the meteorological conditions. Indeed, in order to shelter people, buildings have to be safe, but they also have to provide the basic commodities (water, electric power, heating capacity). The number of buildings and the density of population near a given distribution node (of all utility networks considered in SYNER-G) are then used to estimate a daily demand level in terms of gas, electricity and water supply.

On the other hand, the actual supply of the utility networks needs to be estimated in both normal (pre-event) and degraded situations (post-event), in order to assess whether the buildings are still well supplied, resulting in the potential inhabitability of the related households.

The damage state of the Buildings system has also an impact in terms of heightened demand with respect to emergency services: health-care system (treatment of injuries) and fire-fighting system (due to fires induced by gas leaks or electrical malfunctions, for instance).

Finally, a physical or geographical interaction is also introduced in the model: some buildings may collapse in a way that the resulting debris fall on the road pavement, thus obstructing partially or totally the adjacent road segment (Anastassiadis & Argyroudis, 2007).
1.2.2 Inputs required for the assessment of the performance of the System

There are different levels of analysis which can be used to assess the performance of the building system. A first approach (level I) would be to only assess the connectivity of the building aggregates to supplied distribution nodes of the different systems. However, the shelter model developed in the deliverable D4.7 – Prototype framework for Integration of socio-economic impacts with damage and performance models of the physical systems requires quantitative data from utility systems: the ratio of satisfied to required demand at nodes for each utility (Table 1-1). Thus, a level II analysis, with quantitative indicators, is implemented for some of the systems in the SYNER-G methodology in order to provide necessary inputs to the socio-economic modules.

Table 1-1 Different levels of analysis for the different systems supplying Building systems

<table>
<thead>
<tr>
<th>System</th>
<th>Level I (connectivity)</th>
<th>Level II (serviceability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power Network</td>
<td>Connection to functional EPN supply nodes</td>
<td>Supplied Electrical Power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required Electrical Power</td>
</tr>
<tr>
<td>Gas and Oil</td>
<td>Connection to functional GAS supply nodes</td>
<td>Gas Flow Supplied</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas Flow Required</td>
</tr>
<tr>
<td>Water Supply Network</td>
<td>Connection to functional GAS supply nodes</td>
<td>Supplied Water output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required Water output</td>
</tr>
<tr>
<td>Road Network</td>
<td>Access to RDN nodes</td>
<td>Actual Traffic Demand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required Traffic Demand</td>
</tr>
</tbody>
</table>
1.2.3 Performances indicators of the Buildings system

These indicators are those already presented in Deliverable 2.2:

- **Building damage/collapse.** This indicator estimates the physical damage of the buildings after an earthquake. It is strongly dependent on the type of structure analysed and it describes the probability of a structure to exceed different damage states (such as ‘yielding’ or ‘collapse’ for instance) given a level of ground shaking;

  **Indicators:**
  
  At the cell level:
  - ratio of yielding buildings to total buildings for each building typology
  - ratio of collapsed buildings to total buildings for each building typology

  At the regional level:
  - number of yielding buildings for each building typology
  - number of collapsed buildings for each building typology
  - number of undamaged buildings for each building typology
  - total number of yielding buildings
  - total number of collapsed buildings
  - total number of undamaged buildings

- **Building usability.** This indicator identifies the extent to which a building can be used by the inhabitants, and depends mainly on the physical damage to the structure (building damage/collapse);

  **Indicator:**
  
  At the cell level:
  - ratio of usable buildings to total buildings
  - ratio of fully usable buildings
  - ratio of partially usable buildings

  At the regional level:
  - total number of non-usable buildings
  - total number of partially usable buildings
  - total number of usable buildings

- **Building habitability.** This indicator identifies whether the occupants can inhabit the building, and depends on the building usability and the utility loss (to the building).
D5.1 – Systemic vulnerability and loss for building aggregates in urban scale

Indicator:

At the cell level:
- ratio of habitable buildings to total buildings

At the regional level:
- total number of habitable buildings

- **Casualty model.** This model leads to indicators that estimate the number of deaths and injuries after an earthquake. It depends both on the type of building and on the number of people that live or reside temporarily in the damaged structure;

Indicator:

At the cell level:
- Number of deaths
- Number of severe injuries
- Number of light injuries

At the regional level:
- Number of deaths
- Number of severe injuries
- Number of light injuries

- **Debris model.** This model leads to indicators that estimate the amount of debris following an earthquake. It depends on the building type and on the structural and non-structural damage.

Indicator:

At the cell level
- Number of collapsed buildings per unit of length
- Average height of buildings from each typology
2 Software implementation

2.1 PRELIMINARY PRESENTATION OF THE SYNER-G TOOLBOX

A proof-of-concept toolbox has been developed within Task 2.1 in order to implement the general SYNER-G methodology (see D2.1 – General methodology for systemic seismic vulnerability assessment). It is based on an object-oriented framework, with each infrastructure system being modelled by a specific class. Each class includes some attributes (the data on the studied system, as well as performance indicators) and methods (functions that can be called to compute or update some attributes of the class, like damage states for instance). A low-resolution class diagram is presented below, as more details can be found in Deliverable D2.1:

![Class Diagram](image)

Figure 2-1 General representation of the Infrastructure class within the general framework (Deliverable D2.1)

2.2 ATTRIBUTES OF THE BUILDING CLASS

No building classes are specifically defined. Building related attributes and methodologies are part of the cell and region classes.

Building cells are defined with a list of attributes. Parts of them are initial parameters, which come from databases, and the other ones are derived from computation of the states of the overall system.

2.2.1 Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>parent</td>
<td>Class heritage</td>
</tr>
<tr>
<td>vertices</td>
<td>coordinates of 2 vertices (defining a square cell: NW and SE corners)</td>
</tr>
<tr>
<td>centroid</td>
<td>coordinates of the centroid of the cell</td>
</tr>
<tr>
<td><strong>adjacent cells</strong></td>
<td>pointers to adjacent grid cells</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td><strong>area</strong></td>
<td>total area of the cell</td>
</tr>
<tr>
<td><strong>city</strong></td>
<td>name of the city where the cell is localized</td>
</tr>
<tr>
<td><strong>building typologies</strong></td>
<td>a $n_T \times 1$ vector with the number of buildings in each of the $n_T$ typologies e.g. [M, RC]</td>
</tr>
<tr>
<td><strong>demographic</strong></td>
<td>population living in the cell</td>
</tr>
<tr>
<td></td>
<td>number of households living in the cell</td>
</tr>
<tr>
<td></td>
<td>Population$T_1$ Population living in the $T_1$ typology</td>
</tr>
<tr>
<td></td>
<td>... Population$T_i$ Population living in the $T_i$ typology</td>
</tr>
<tr>
<td><strong>economic</strong></td>
<td>Number of people working in retail activities</td>
</tr>
<tr>
<td></td>
<td>Number of people working in service activities</td>
</tr>
<tr>
<td></td>
<td>average unemployment rate in the cell</td>
</tr>
<tr>
<td><strong>social</strong></td>
<td>a 4x1 vector of percentage of usage in each of the types Green, Residential, Commercial and Industrial</td>
</tr>
<tr>
<td><strong>bldg usage</strong></td>
<td>pointers to the WSN Demand nodes supplying the cell</td>
</tr>
<tr>
<td><strong>reference nodes WSN</strong></td>
<td>pointers to the EPN Demand nodes supplying the cell</td>
</tr>
<tr>
<td><strong>reference nodes EPN</strong></td>
<td>pointers to the RDN nodes connecting the cell to the road Network</td>
</tr>
<tr>
<td><strong>reference nodes RDN</strong></td>
<td>pointers to the GAS Demand nodes supplying the cell</td>
</tr>
<tr>
<td><strong>builtup area</strong></td>
<td>Area of the total built surface, with floors taken into account (m²)</td>
</tr>
<tr>
<td><strong>Water demand</strong></td>
<td>Flow of water required by the cell in normal conditions</td>
</tr>
<tr>
<td><strong>Power demand</strong></td>
<td>Electrical Power required by the cell in normal conditions</td>
</tr>
<tr>
<td><strong>built</strong></td>
<td>0 if there is no buildings in the cell 1 if there are buildings in the cell</td>
</tr>
<tr>
<td><strong>resistance to evacuation (RE)</strong></td>
<td>[0;1], quantitative indicator regarding the proclivity to evacuate after a disaster: from 0 = willingness to evacuate to 1 = refusal</td>
</tr>
<tr>
<td><strong>states</strong></td>
<td>Distance from the seismic source to the centroid of the cell</td>
</tr>
<tr>
<td><strong>Primary IMs</strong></td>
<td>Primary Intensity measures at the centroid of the cell</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td><strong>local IMs</strong></td>
<td>Intensity measures at the cell centroid, taking into account local site effects</td>
</tr>
<tr>
<td><strong>Damage Ti</strong></td>
<td>Average damage state of the buildings of typology Ti [none, yielding, collapse]</td>
</tr>
</tbody>
</table>
| **UL_WSS**      | Diminution of the quantity of water delivered to the cell: \[
\frac{\text{SuppliedWaterOutput}}{\text{RequiredWaterOutput}} [0;1]
\] |
| **UL_EPN**      | Diminution of the quantity of electrical power delivered to the cell: \[
\frac{\text{SuppliedElectricalPower}}{\text{RequiredElectricalPower}} [0;1]
\] |
| **UL_GAS**      | Diminution of the quantity of gas delivered to the cell: \[
\frac{\text{SuppliedGasFlow}}{\text{RequiredGasFlow}} [0;1]
\] |
| **UL_total**    | Diminution of the aggregated quantity of utility services delivered to the cell, weighted according to the socio-economic module:
\[
\text{UL}_{\text{total}} = w_{\text{EPA}} \times \text{UL}_{\text{EPA}} + w_{\text{WSS}} \times \text{UL}_{\text{WSS}} + w_{\text{GAS}} \times \text{UL}_{\text{GAS}} [0;1]
\] |
| **UL_RDN**      | Diminution of the road accessibility in the cell \[
\frac{\text{PossibleTrafficFlow}}{\text{RequiredTrafficFlow}}
\] |
| **Nfu** | Number of fully usable buildings in the cell |
| **Npu** | Number of partially usable buildings in the cell |
| **Nnu** | Number of non-usable buildings in the cell |
| **NHfugw** | Percent of fully usable buildings that are non-habitable, where \( \text{UL} \geq \text{UL}_T \), for good weather |
| **NHfubw** | Percent of fully usable buildings that are non-habitable, where \( \text{UL} \geq \text{UL}_T \), for bad weather |
| **NHpugw** | Percent of partially usable buildings that are non-habitable, where \( \text{UL} \geq \text{UL}_T \), for good weather |
| **NHpubw** | Percent of partially usable buildings that are non-habitable, where \( \text{UL} \geq \text{UL}_T \), for bad weather |
| **weight EUA** | Proportion of EUA objects inside the cell, to distribute the EUA indicators among the intersected cells (e.g. projection weight). |
| **weight LUP** | Proportion of LUP objects inside the cell, to distribute the LUP indicators among the intersected cells (e.g. projection weight). |
| **weight BC** | Proportion of BC objects inside the cell, to distribute the
2.3 METHODS USED IN THE BUILDING CLASS

Different methods have to be implemented in the SYNER-G tool to compute the different indicators required for the assessment of the Building aggregates performances. The different purposes are described in the chapter 3 of Deliverable 2.2, so only the structures of these methods are described below.

2.3.1 Project Building Census (BC) data into the cell

<table>
<thead>
<tr>
<th>projectBCData</th>
<th>Cell, Building area, Corners of the cell</th>
<th>Built-up area, Building typologies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This method projects the building database into the cells. It interpolates the number of buildings from the different types, from building census, in the cell. The calculation is based on weighted averages, with weights determined by ratio of areas. The following description represents the ideal cases, where all the different data exist. If not, the calculations for lacking data are not performed and the corresponding indicators are not given.

**Case 1: Number of buildings and Households (Figure 2-2)**

![Diagram showing data interpolation for building census](image)

- BCi: Homogeneous zone number i
- Ai: Area of the BCi
- Mi: number of masonry buildings in BCi
- RCi: number of Reinforced concrete buildings in BCi
- H_Mi: number of households in masonry buildings in BCi
- H_RCi: number of households in RC buildings in BCi
- ai: area of the intersection of BCi and the cell
- M: number of masonry buildings in the cell
- RC: number of reinforced concrete in the cell
- TotBDG: total number of buildings in the cell
- H_M: number of households in masonry building in the cell
- H_RC: number of households in RC buildings in the cell
- H_tot: total number of households in the cell

The corresponding equations are:

Number of buildings and Households (Figure 2-2)
Case 2: Habitable surfaces in BCi:

If the Building Census contains information on habitable surface per typology, then computation of habitable surface per typology in the cell can be performed (Figure 2-3).

\[ M = \sum M_i \times \frac{a_i}{A_i} \]
\[ RC = \sum RC_i \times \frac{a_i}{A_i} \]
\[ TotalBDG = M + RC \]
\[ H_M = \sum H_M_i \times \frac{a_i}{A_i} \]
\[ H_RC = \sum H_RC_i \times \frac{a_i}{A_i} \]
\[ H_{tot} = H_M + H_RC \]

The corresponding equations are:

Case 3: Building footprints areas per typology and number of floors in BCi:

This case is close to the case 2. Habitable surface per typology is obtained by multiplying the building footprints areas by the number of floor per typology (Figure 2-4).
The corresponding equations are:

\[
S_M = \sum F_{Mi} \times l_{Mi} \times \frac{a_i}{A_i}
\]

\[
S_RC = \sum F_{RCi} \times l_{RCi} \times \frac{a_i}{A_i}
\]

\[
S_{tot} = S_M + S_RC
\]
2.3.2 Project European Urban Audit (EUA) census data into the cell

This method projects the European Urban Audit database (organized in sub-city districts) into the cells. It interpolates the socio economic parameters from the database into the cell, based on weighted average, with weights determined with ratio of respective areas (Figure 2-9).

There are different cases, according to the available data.

**Case 1:** Number of households per typology and average number of inhabitants per households. (Figure 2-7)

The corresponding equations are thus:

\[ P_{m} = \sum P_{Hi} \times \frac{a_{i}}{\sum a_{i}} \times H_{M} \]

\[ P_{rc} = \sum P_{Hi} \times \frac{a_{i}}{\sum a_{i}} \times H_{RC} \]

\[ P_{t} = P_{m} + P_{rc} \]

NB: if average population per household is not given in each EUA, an average value for the whole region can be used.

**Case 2:** Habitable surface per typology and population. (Figure 2-8)
i: number of the EUA object
Ai: area of EUA #i
Pi: Population of EUA #i
ai: area of the intersection of EUAi and the cell.
S_M: habitable surface in masonry buildings in the cell
S_RC: habitable surface in concrete buildings in the cell
S_tot: Number of buildings in the cell
Pt: total population living in the cell
Pm: population living in masonry buildings in the cell
Prc: Population living in Reinforced Concrete Buildings in the cell

Figure 2-8: Illustration of data interpolation for European Urban Audit database
(Case 2: habitable surface)

\[ Pm = \sum P_t \times \frac{a_i}{\sum a_i} \times S_M \]
\[ Prc = \sum P_t \times \frac{a_i}{\sum a_i} \times H_RC \]
\[ Pt = Pm + Prc \]

**Case 3: Number of buildings per typology and population** (Figure 2-9)

i: number of the EUA object
Ai: area of EUA #i
Pi: Population of EUA #i
ai: area of the intersection of EUAi and the cell.
M: Number of masonry building in the cell
RC: Number of reinforced concrete buildings in the cell
TotalBDG: Number of buildings in the cell
Pt: total population living in the cell
Pm: population living in masonry buildings in the cell
Prc: Population living in Reinforced Concrete Buildings in the cell

Figure 2-9: Illustration of data interpolation for European Urban Audit database
(Case 3: typology)

The corresponding equations are:

\[ Pt = \sum P_t \times \frac{a_i}{\sum a_i} ; Pm = Pt \times \frac{M}{TotalBDG} ; Prc = Pt \times \frac{RC}{TotalBDG} \]

The same method applies for other socio economic indicators (average size of household, employment rate, repartition of the working population among working sectors,...).
Figure 2-10: Example of projection of EUA data on grid cells (from Little Italy Test Case)

Figure 2-11: Projection of population to the cells (population density per km²)

<table>
<thead>
<tr>
<th>Population</th>
<th>9744</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>4061</td>
</tr>
<tr>
<td>Population and Masonry</td>
<td>6430</td>
</tr>
<tr>
<td>PopulationRC</td>
<td>3314</td>
</tr>
</tbody>
</table>
Figure 2-12: Example of results of the *projectEUAd* method for one cell of Little Italy
2.3.3 Project Land Use Plan (LUP) data into the cell

This method projects the Land Use Plan database into the cells. It interpolates the proportion of the cell used by the 4 considered land uses (Residential, Industrial, Commercial and Green area). It is based on weighted averages, with weights computed according to respective areas.

\[ i: \text{number of the LUP object} \]
\[ a_i: \text{area of the intersection of LUP} # i \text{ and the cell.} \]
\[ A: \text{area of the cell} \]
\[ G: \text{Percentage of the cell covered by green areas} \]
\[ R: \text{Percentage of the cell covered by residential areas} \]
\[ I: \text{Percentage of the cell covered by industrial areas} \]
\[ C: \text{Percentage of the cell covered by Commercial area} \]

The corresponding equations are:

\[ R = \frac{\sum a_i}{R_{\text{Residential}}} \]
\[ I = \frac{\sum a_i}{I_{\text{Industrial}}} \]
\[ G = \frac{\sum a_i}{G_{\text{Green}}} \]
\[ C = \frac{\sum a_i}{C_{\text{Commercial}}} \]

Figure 2-13: Illustration of data interpolation for Land Use Plan database

Figure 2-14: Example of projection of LUP data on grid cells (from Little Italy Test Case)
2.3.4 Evaluate Building damages

<table>
<thead>
<tr>
<th><strong>evaluateBLDGdamage</strong></th>
<th>[kEvents, fragility]</th>
<th>damage state</th>
</tr>
</thead>
<tbody>
<tr>
<td>For each typology, the probability for each damage state is given by the fragility sets and the IM value. The damage state is then sampled by using a standard uniform variable.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Description can be found in Deliverable 2.2 chapter **3.1 Building Damage Collapse**

“The evaluateBuildingDamage method is illustrated qualitatively in Figure 2-15. The damage state is determined for all buildings within each typology by sampling a standard uniform variable $u$. The value of $u$, between 0 and 1, falls within one and only one of the intervals defined, at the intensity value obtained for the cell centroid from the seismic hazard model, by the sets of fragility curves for increasing damage states stored for the specific typology (Deliverable 3.1 Fragility functions for common RC and Deliverable 3.2 Fragility functions for masonry buildings in Europe). This is the damage state of the buildings of this type within this cell for the event.”

![Figure 2-15: Illustration of the evaluateBLDGdamage method](image)

For a PGA = 0.295 g

Yielding — Collapse
Figure 2-16: Results of the `evaluateBLDGdamage` method on Masonry Buildings on Little Italy test case, with a M=7.1 Earthquake

Figure 2-17: Results of the `evaluateBLDGdamage` method on reinforced Concrete Buildings on Little Italy test case, with a M=7.1 Earthquake
Damage on Masonry buildings on city #2
Damage on RC buildings on city #2
Attributes for buildings damage for one cell (circled)

Figure 2-18: Example of results of the evaluateBLDGdamage method for one cell of Little Italy test case, for a M=7.1 Earthquake
2.3.5 Evaluate Casualties

At the cell level, this method checks the damage state of each typology present and gives the resulting ratios of deaths and injuries, based on some empirical tables.

### Table 2-1 Examples of casualties ratios organised by damage state and building typology (Zuccari & Cacace, 2011)

<table>
<thead>
<tr>
<th>Ratios</th>
<th>Damage states</th>
<th>Typology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D0</td>
<td>D1</td>
</tr>
<tr>
<td>deaths</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>injuries</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Several casualties models have been proposed in previous studies, e.g. Zuccaro & Cacace (2011), Coburn & Spence (2002), Spence & So (2010), ELER (Erdik et al., 2008) and ATC-13 (HAZUS). A new model is currently under development within SYNER-G (D4.7 - Prototype Framework for Integration of Physical and Socio-economic Models for Estimating Shelter Needs and Health Impacts in Earthquake Disasters) and it is based on three building-casualty superclasses (i.e. building categories including several typologies) and the use of macroseismic intensity as a refinement of the sole damage state. This casualties model is calibrated with the analysis of 3 historic events: Friuli 1976, Irpinia 1980 and L’Aquila 2009.

Whatever the casualties model chosen by the user, the general procedure remains the same: using the casualties ratios, the number of deaths and injuries is obtained by multiplying the ratios by the number of buildings from each typology and by the number of occupants within each building of each typology. The number of occupants is by default the population living in each typology, yet it is possible to specify also an “occupancy coefficient”, based on the proportion of the population that is actually indoors, depending on the time of the day and the type of activities located within the cell (Residential, Commercial or Industrial).

The results for each typology are then aggregated at the cell level to give the number of deaths and injuries in each cell. Finally, at the region level, the number of deaths and injuries are summed over all the cells to give the casualties estimations for the whole city or region.
Figure 2-19: Results of the evaluate_casualties method on number of deaths per cell on Little Italy test case, with a M=7.1 Earthquake

Figure 2-20: Results of the evaluate_casualties method on number of injuries per cell on Little Italy test case, with a M=7.1 Earthquake
<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>deathMasonry</td>
<td>273</td>
</tr>
<tr>
<td>injuredMasonry</td>
<td>956</td>
</tr>
<tr>
<td>deathRC</td>
<td>0</td>
</tr>
<tr>
<td>injuredRC</td>
<td>0</td>
</tr>
<tr>
<td>death</td>
<td>273</td>
</tr>
<tr>
<td>injured</td>
<td>956</td>
</tr>
</tbody>
</table>

Figure 2-21: Example of results of the `evaluate_casualties` method for one cell of Little Italy
2.3.6 Evaluate Building usability

<table>
<thead>
<tr>
<th>evaluate_building_usability</th>
<th>damage states</th>
<th>FU, PU or NU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on a table (Table 2-2) giving correspondence between damage levels and usability classes:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- FU: fully usable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- PU: partially usable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- NU: non-usable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Description of this method can be found in Deliverable 2.10 and Deliverable 4.7:

“The evaluateBuildingUsability method is based on a simplified semi-empirical approach by which building usability is derived from estimates of building damage rates for three building usability classes. Buildings can be either immediately non usable (NU), partially usable (PU) or fully usable (FU) as a function of severity of damage and an empirically-derived Usability Ratio (UR).”

| Table 2-2 Example of Building Usability repartition according to Damage State |
|-----------------------------|-----------------------------|
| Usability Ratio (UR)        | Damage Level               |
|                            | none | yielding | collapse |
| Fully Usable               | 0.87 | 0.22     | 0.00      |
| Partially Usable           | 0.13 | 0.25     | 0.02      |
| Non Usable                 | 0.00 | 0.53     | 0.98      |

The number of building in each usability level is computed as follow:

\[
N_{fu_t} = UR_{FU \text{none}} \times N_{nont} + UR_{FU \text{yielding}} \times N_{yield} + UR_{FU \text{collapse}} \times N_{collapse}
\]

\[
N_{pu_t} = UR_{PU \text{none}} \times N_{nont} + UR_{PU \text{yielding}} \times N_{yield} + UR_{PU \text{collapse}} \times N_{collapse}
\]

\[
N_{nu_t} = UR_{NU \text{none}} \times N_{nont} + UR_{NU \text{yielding}} \times N_{yield} + UR_{NU \text{collapse}} \times N_{collapse}
\]

With:
- \( t \) = building type (Masonry, RC,...)
- \( i \) = damage state (none, yielding, collapse)
- \( N_{i_t} \) = Number of buildings of type \( t \) in damage state \( i \), in the cell
- \( N_{fu_t}, N_{pu_t}, N_{nu_t} \) = Number of buildings of type \( t \) respectively fully, partially and non-usable

Thus

\[
N_{fu} = \sum_t N_{fu_t}
\]

\[
N_{pu} = \sum_t N_{pu_t}
\]

\[
N_{nu} = \sum_t N_{nu_t}
\]
Figure 2-22: Example of results of the `evaluate_building_usability` method for one cell of Little Italy Test Case, for a M=7.1 Earthquake

<table>
<thead>
<tr>
<th>Nfu</th>
<th>4287</th>
</tr>
</thead>
<tbody>
<tr>
<td>Npu</td>
<td>2037</td>
</tr>
<tr>
<td>Nnu</td>
<td>3407</td>
</tr>
</tbody>
</table>
2.3.7 Get Utility losses

**get_utility_loss** from reference nodes WSS/EPN/GAS

UL is the weighted mean of the specific utility losses for WSN, EPN and GAS. *get_utility_loss* method gets the performance indicators of the different systems WSS, EPN and GAS, at the corresponding reference nodes of the cell, and divides it with the corresponding demand to compute the utility losses at the cell for each system.

Then, these Utility Losses are aggregated thanks to a weighted mean, to obtain a unique index, the total Utility Loss, based on this formula:

\[
UL_{tot} = w_{EPN} \times UL_{EPN} + w_{WSS} \times UL_{WSS} + w_{GAS} \times UL_{GAS}
\]

Default weights proposed in Deliverable 2.1 are given in Table 2-3.

<table>
<thead>
<tr>
<th>Weight factor</th>
<th>Default values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(w_{EPN})</td>
<td>0.5</td>
</tr>
<tr>
<td>(w_{WSS})</td>
<td>0.2</td>
</tr>
<tr>
<td>(w_{GAS})</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2-3 Default values for Utility losses weight factors

Figure 2-23: Result of the *get_utility_loss* method for the water Supply System (UL\(_{WSS}\) = 1 – HR). HR is the head ratio for each cell, assigned to a given demand node (or distribution node).
Figure 2-24: Example of results of the `get_utility_loss` method for one cell of Little Italy, for a M=7.1 Earthquake scenario (Water Supply System being the only network considered)
2.3.8 Evaluate Building habitability

<table>
<thead>
<tr>
<th>evaluate_building_habitability</th>
<th>building usability, utility loss, weather</th>
<th>H or NH</th>
</tr>
</thead>
</table>
| A non-usable (NU) building is automatically non-habitable (NH).
For FU and PU buildings, a table (example givenTable 2-4) gives the utility loss threshold (UL<sub>T</sub>) that is acceptable (based on weather conditions) for the building to be considered habitable (H). If UL > UL<sub>T</sub>, then the building becomes Non Habitable (NH). Utility loss is obtained from the get_utility_losses method. |
| **Table 2-4 Example of values for Utility Losses Threshold** |
| Utility Loss Tolerance Threshold | Weather Condition | |
| | Good | Bad |
| FU | 1.0 | 0.1 |
| LU | 0.9 | 0.0 |
| Description of this method can be found in Deliverable 4.7. Results are provided as percentage of Non Habitable Buildings in the cell. |

Figure 2-25: Example of results of the evaluate_building_habitability method for one cell of Little Italy Test Case, for a M=7.1 Earthquake
### 2.3.9 Get Building impacts on road network

<table>
<thead>
<tr>
<th>\textit{get_buildings_impacts_on_RDN}</th>
<th>[states]</th>
<th>Equivalent linear buildings density, building damage states and building heights</th>
</tr>
</thead>
</table>
This method provides the useful information on buildings to assess the impact of the building system on the functionality of the road network.

**Building heights per typology:**
This computation is similar to the ones in ProjectBCData.

![Diagram of building classification](image)

- BCi: Homogeneous zone number i
- $h_{Mi}$: average height of masonry buildings in BCi
- $h_{RCi}$: average height of RC buildings in BCi
- $a_i$: area of the intersection of BCi and the cell
- M: number of masonry buildings in the cell
- H: number of RC buildings in the cell
- $h_{M}$: average height of masonry building in the cell
- $h_{RC}$: average height of RC buildings in the cell

**Figure 2-26: Illustration of data interpolation for building census (Buildings height)**

The corresponding equations are:

$$h_{M} = \sum h_{M} \cdot \frac{a_i}{A_i}$$

$$h_{RC} = \sum h_{RC} \cdot \frac{a_i}{A_i}$$

**Equivalent linear density of buildings**
In order to have an estimation of the number of building edges that are likely to board a road segment of a given length within the cell, an equivalent linear density of buildings needs to be approximated, using this equation:

With
- $A$: area of the cell
- $B$: number of buildings in the cell
- $d_{li}$: equivalent linear density of buildings

$$d_{li} = \sqrt{\frac{B}{A}}$$

This calculation is based on the assumption that buildings have footprints' shape close to squares. Otherwise, a spatial analysis is to be done in order to compute the building density along a direction of interest (e.g., following the general orientation of the studied road segments, for instance): this could be done at the GIS level and then a projection of the different linear densities of buildings should be aggregated into the cells.

**Complete collapse of buildings**
The building collapses that are calculated using the fragility curves do not systematically represent the “complete” collapses, as they include also local failures that do not necessarily result in a complete collapse of the structure. However, the complete collapses can be estimated from the collapse state given by fragility curves, using a corrective empirical factor $\mu$, which gives the proportion of buildings in collapse state (through the fragility analysis).
that are actually completely collapsed. This factor depends on the typology as well as the seismic intensity. For each typology, it is then possible to compute the number of totally collapsed buildings, using the following equations:

With:

$RC_C$: number of RC buildings in the collapse state  
$M_C$: number of masonry buildings in the collapse state  
$RC_{CC}$: number of completely collapsed RC buildings  
$M_{CC}$: number of completely collapsed masonry buildings  
$\mu_{RC}$: corrective factor for RC buildings (for instance, $\mu=0.1$)  
$\mu_{M}$: corrective factor for masonry buildings (for instance, $\mu=0.5$)

$$RC_{CC} = \mu_{RC} \cdot RC_C \quad \text{and} \quad M_{CC} = \mu_{M} \cdot M_C$$

2.4 FLOWCHART

All these methods are chained (Figure 2-27) in order to compute the different performances indicators of the building aggregates systems.

Figure 2-27 Flowchart of the Building class computation
3 Probabilistic assessment of road closure due to building collapses – Proposition of a compatible framework with the SYNER-G methodology

1. GENERAL FRAMEWORK

This procedure is applied at the cell level, for each segment of the road network, projected into the cell (see D2.1 for mesh generation and projection of data on cells). The final result (Figure 3-1) gives the probability of exceeding a given functionality level along the road segment. It is thus possible to get the probability of road closure for each road segment crossing a given cell (at the price of very large approximations, though).
This model uses the following data from buildings, which should be available at the cell level:

- Percentage $P_i$ of each typology $T_i$;
- Avg. height $Y_i$ of each typology $T_i$ (e.g. low, medium or high rise);
- Damage state of each typology: $C_i = 1$ if collapse and $C_i = 0$ if not;
- A corrective empirical factor $\mu_i$, which gives the proportion of buildings in collapse state (through the fragility analysis) that are actually completely collapsed.
- A linear density $d_l$ of buildings within the cell: this could be done by a rough spatial analysis of the studied area, using a GIS map of buildings (if available) or some satellite images. This is necessary in order to know how many buildings are likely to be found along a given length.

On the other hand, the following data should be available on the road network:

- Length $L$ of the projected road segment in the cell;
- Width $W_r$ (or number of lanes) of the road segment;
- Whether the road segment is surrounded by buildings. We can then set a virtual length $L'$, taking the following values: $L' = 2L$ if buildings on both sides of the road, $L' = L$ if buildings on one side only, $L' = 0$ if no building (open area).
- The average distance $W_{br}$ between the buildings and the road segment (again, this should be done using some satellite images or a field survey). An average assessment could be done at the level of each building census area (homogeneous zones) and then aggregated at the cell level;

\[
\text{Nb of completely collapsed buildings along road segment: } \frac{k}{100} \cdot L' \sum \mu_i \cdot C_i \cdot P_i
\]
We also need to estimate $N_t$, the number of completely collapsed buildings of each typology that are present along the road segment of length $L$. Using Figure 3-2, we can compute the following:

$$N_t = L \cdot \mu_t \cdot C_t \cdot P_t \cdot d_l$$

Using the approach by Argyroudis (2010), we can then use $W_r$, $W_{br}$ and $Y_i$ to compute the exceedance probability of functionality level $FL_j$, when a single building of typology $T_i$ collapses along the road segment: $P(\geq FL_j|Y_i)$

Finally, if we note that a single building collapse is enough to induce a road blockage (corresponding to a fault-tree analysis with all building collapses counting as OR gates), the global exceedance probability of functionality level $FL_j$ along the road segment can then be written as (for $n$ typologies in the cell):

$$P_{fl}(\geq FL_j) = 1 - \prod_{i=1}^{N} [1 - P(\geq FL_j|Y_i)]^{ni}$$

### 2. PROBABILITY OF ROAD CLOSURE GIVEN A SINGLE COMPLETE COLLAPSE

The probability of road closure given the complete collapse of a single building relies on many parameters:

- $W_r$, the width of the road pavement;
- $W_{br}$, the width between the building and the road;
- $W_d$, the width of the debris heap resulting from the collapse of the building;
- $W_{fr}$, the width of the road that remains free after the debris fall;

The width $W_r$ of the road is an input data that should be available from GIS files and an analysis of satellite images, for instance. The width $W_{br}$ could be also directly estimated, through field survey or satellite images, or it could be estimated from the average distance $W_{bb}$ between buildings across the road (see Figure 3-3):

$$W_{br} = \frac{W_{bb} - W_r}{2}$$
The width $W_d$ occupied by the debris resulting from the collapse can be estimated through various empirical models, which depend mostly on the typology and the height of the building. In a probabilistic framework, we can define a probability of exceedance of $W_d$, e.g. $P(W_d \mid Y_i)$, given the height of the building (directly related to the typology, via the number of stories for instance). If we assume a normal distribution, the mean expected value $E[W_d]$ can be computed by some empirical models, e.g. Argyroudis (2003), Tung (2004) or Goretti (2005). Argyroudis (2011) proposes various collapse models, whether the buildings belong to an aggregate or is free to collapse in both directions for instance: coefficients of variation for some parameters are also defined, in order to compute the standard deviation of $W_d$.

It is then possible to evaluate the width $W_r$ of the road that remains after the debris fall:

$$E(W_{fr}) = \min[W_{fr} + W_{br} - E(W_d)]$$

Finally, we use the probability of exceedance $P(W_{fr} \mid Y_i)$ to compute the probability of exceeding a given functionality level, e.g. $P(FL_j \mid Y_i)$. The functionality levels are defined by using some specific values of $W_{fr}$, according to the number of lanes still open or the type of traffic allowed (emergency vehicles).

<table>
<thead>
<tr>
<th>Functionality levels</th>
<th>$W_{fr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL₀</td>
<td>Open</td>
</tr>
<tr>
<td>FL₂</td>
<td>Open for emergency</td>
</tr>
<tr>
<td>FL₃</td>
<td>Closed</td>
</tr>
</tbody>
</table>

Table 3-1: Proposed values for defined functionality levels

3. **ESTIMATION OF NUMBER OF BUILDINGS ALONG ROAD LENGTH**

+ **Option 1:**

In order to estimate the number of buildings that are likely to be located on one side of a road segment of length $L$, a possible approach is to evaluate a linear density of buildings at the cell level. Thanks to $A_i$, the area of the cell (given by the SYNER-G toolbox, through the
dimensions of each square) and \( N_b \) the number of buildings within the cell (previously computed by the toolbox, through the projection on cells), we can approximate a linear density of buildings:

\[
d_l = \sqrt[2]{\frac{N_b}{A_l}}
\]

This procedure represents an efficient way to compute the linear density of buildings’ edges in a rough approximation: yet, its accuracy depends highly on the shape of buildings and the uniformity of the repartition of buildings in the cell.

**+ Option 2:**

If the occupied volume per person is available at the cell level (through the computation of the number of persons per household and the number of households per building type), it is also possible to have an estimation of the building linear density through the following relation:

\[
d_l = \sqrt[2]{\frac{H \cdot N_b}{N_{hp} \cdot V}}
\]

\( H \) is the building height and \( N_b \) the total number of buildings within the cell. \( N_{hp} \) is the number of inhabitants within the cell, and \( V \) the volume occupied by each inhabitant.

**+ Option 3:**

Another approach by Tung (2004) proposes to assess directly a linear density of collapsed buildings, using the following parameters:

- \( A_b \): total area of buildings (footprints area) within the cell (or homogeneous zone);
- \( N_b \): total number of buildings within the cell (or homogeneous zone);
- \( N_{cb} \): number of collapsed buildings within the cell (or homogeneous zone);

\( A_c \), the area of collapsed buildings within the cell (or homogeneous zone), is then:

\[
A_c = \frac{N_{cb}}{N_b} A_p
\]

\( P_A \), the collapse density by area, is then computed using \( A_c \), the total area of the cell:

\[
P_A = \frac{A_c}{A_t}
\]

It is then possible to evaluate the linear density of collapsed buildings (\( P_L \), per length unit):

\[
P_L = k \sqrt[2]{\frac{A_c}{A_t}}
\]

The corrective factor \( k \) is introduced by Tung (2004) and it accounts for the difference between the density of buildings along the road segment, and the density of buildings in the considered area (cell or homogenous zone). This comparison between both densities has to
be performed using satellite images or footprints, at the scale of building census zones for instance (see Figure 3-5).

The following values of $k$ are proposed:
- $k=0.9$: density along the road is less than areal density;
- $k=1$: density along the road is equal to areal density;
- $k=1.1$: density along the road is a bit higher than areal density;
- $k=1.2$: density along the road is much higher than areal density;

The approach described above is more elaborate and may lead to more accurate results than the one proposed for SYNER-G. However, it requires additional data that may not be always available: building footprints to compute the areas, estimation of the factor $k$ (manual analysis for each building census zone).

+ Option 4:

Finally, in order to evaluate the number $N_{bld}$ of buildings along a road segment of length $L$, Goretti & Sarli (2006) propose to rely on a percentage of built road length, $\alpha_{ed}$, and the mean building length, $l_{bld}$:
\[ N_{bld} = \frac{2L_{\alpha_{ed}}}{l_{bld}} \]

The factor 2 is introduced to account for buildings that are on both sides of the road. The main limitations of this approach reside again in the difficulty to estimate the parameters \( \alpha_{ed} \) and \( l_{bld} \), which require very detailed data (building footprints) and a careful spatial analysis of each building census zone.
References


Washington, DC, USA.


