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# 1 Technical references

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## 2 Abstract

This study presents an integrated framework for seismic risk mitigation and economic evaluation applied to the Campi Flegrei area, based on a detailed building-by-building exposure database. The methodology follows the classical risk chain—hazard, exposure, vulnerability, and damage—and extends it to include a consistent cost–benefit analysis within a probabilistic framework. Instead of adopting deterministic scenarios, multiple hazard levels associated with different probabilities of exceedance over a 50-year horizon are considered, ensuring coherence with national hazard estimates and supporting long-term planning.

Building vulnerability is modelled through Damage Probability Matrices (DPMs), which relate macroseismic intensity (IMCS) to expected damage distributions. From these distributions, the number of collapsed and unusable buildings is derived, and restoration costs are estimated using representative unit costs per damage level. Indirect costs are assumed as a percentage of direct costs, and future post-seismic losses are discounted to present value to ensure comparability with immediate mitigation investments.

Three progressive mitigation phases are defined, targeting the most vulnerable classes (A and B): (1) restoration of material capacity, (2) installation of tie rods, and (3) structural strengthening. After each phase, the vulnerability distribution is updated and expected impacts recalculated, allowing the quantification of cumulative benefits in terms of damage and loss reduction.

Application to Campi Flegrei shows that while higher mitigation levels lead to greater physical damage reduction, intermediate interventions often provide the most favourable cost–benefit balance, particularly at moderate-to-high seismic intensities. The framework thus offers a structured tool for risk-informed prioritization and resilient urban planning.

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## 3.1 List of tables

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# 4 Development of a tool to support the decision makers in the framework of DRR and CCA integrated activities on the base of Cost- benefit analyses and Multi-Criteria techniques

The assessment of costs relies on a structured set of information that directly derives from the logical chain typical of risk analyses. Within this framework, costs represent the outcome of a process that starts with the characterization of the hazard, proceeds through the description of exposure and vulnerability, and ultimately leads to the estimation of expected damage. When addressing the issue of costs, it is necessary to consider a structured set of information that directly derives from the logical chain typical of risk analyses. In this framework, costs represent the outcome of a process that starts with the characterization of the hazard, proceeds through the description of exposure and vulnerability, and ultimately leads to the estimation of expected damage.

First, **direct costs** are identified, which are associated with reconstruction and/or restoration activities of the exposed elements damaged because of a seismic event. These are complemented by **indirect costs**, mainly related to emergency management and the interruption of economic and social activities, which are generally estimated as a percentage of the direct costs. In addition, **mitigation costs** may be considered when risk reduction strategies are implemented in the pre-event phase (so-called "peace time").

The activity proposed in this section therefore includes:

- the **estimation of mitigation costs in the pre-seismic phase**, associated with interventions aimed at reducing vulnerability or exposure;
- the estimation of direct and indirect costs in the post-seismic phase, derived from the expected damage to the exposed elements.

Since the objective is a comprehensive risk assessment, the analyses do not refer to specific deterministic scenarios, but rather take the form of **probabilistic risk analyses**, applied to contexts for which sufficient information on the exposed assets is available. The **reference exposure model** is therefore the one described in Deliverable 3.6.1, which provides the informational basis for damage quantification and, consequently, for the estimation of associated costs.

## 4.1 Mitigation strategies

The definition of **mitigation interventions** requires, as a first step, a detailed analysis of the **exposure database**, aimed at identifying the most recurrent vulnerability features within the analyzed building stock. When survey data are available, this analysis allows the systematic identification of dominant vulnerability elements, which form the basis for the planning of mitigation actions.

Based on the selection of vulnerability elements identified within the **SAVE procedure (Zuccaro and Cacace 2015)**, it is possible to define a **multi-phase mitigation strategy**, characterized by standardized and progressive interventions. By way of example, a first phase may include interventions on the oldest buildings, aimed at restoring the mechanical properties of construction materials; a second phase may involve the installation of tie rods in buildings where they are absent; a third phase may finally address the strengthening of specific structural elements.

At the end of each intervention phase, a **reclassification of seismic vulnerability** is performed for the affected buildings, to update the exposure model. Since the surface area and height of each building are known, **intervention costs** can be estimated by applying an **average unit cost per square meter**, defined according to the type of intervention considered.

Updating the exposure map after each intervention phase makes it possible to repeat the **impact assessment**, evaluating the resulting changes in the expected damage levels of the buildings. Based on the average restoration cost per square meter associated with each damage level, **direct and indirect costs** can then be estimated for each intervention phase.

Finally, through the **discounting of direct costs**, cumulative **total costs** can be estimated and the economic benefit associated with the progressive implementation of mitigation measures can be assessed. This approach allows the identification of the **optimal intervention phase**, i.e. the level beyond which further mitigation actions are no longer economically convenient in terms of risk reduction.

## 4.2 Costs analyses

### 4.2.1 Mitigation costs

Mitigation costs are estimated by grouping the interventions into the three mitigation phases defined in the study, each characterized by an **average unit cost per square metre**, representative of the expected works.

For each phase, total mitigation costs are obtained by applying the corresponding unit costs to the surface area of the buildings identified in the exposure database.

### 4.2.2 Estimation of post-seismic direct and indirect costs

Post-seismic costs are divided into **direct costs**, related to repair or reconstruction of damaged buildings, and **indirect costs**, associated with emergency management and functional losses. Indirect costs are assumed to be equal to **50% of direct costs**.

The total cost is therefore defined as in Equation (1):

$$C_{\mathrm{TOT}} = C_{\mathrm{mit}} + C_{\mathrm{dir}} + C_{\mathrm{ind}} \tag{1}$$

### 4.2.3 Cost discounting and comparison

To consistently compare **pre-seismic mitigation costs**, incurred immediately, with **post-seismic restoration or reconstruction costs**, which may occur in the future, a **discounting procedure** is applied. This allows all economic estimates to be referred to a common time horizon, ensuring comparability among different phases and cost components.

Direct and indirect post-seismic costs are assumed to occur **50 years in the future** and are therefore discounted to present value using an appropriate discount rate $i$:

$$(C_{\text{dir}} + C_{\text{ind}})_{\text{today}} = \frac{C_{\text{dir}} + C_{\text{ind}}}{(1+i)^{50}} \tag{2}$$

The total present cost is given by the sum of mitigation costs and discounted post-seismic costs:

$$C_{\text{TOT}} = C_{\text{mit}} + (C_{\text{dir}} + C_{\text{ind}})_{\text{today}} \tag{3}$$

## 4.3 Index definitions

### 4.3.1 Damage index

The **damage index** adopted in this study is conceived as a synthetic measure aimed at integrating, within a single metric, information related to the **observed damage levels** of exposed buildings resulting from the occurrence of a seismic event. Unlike the vulnerability index, which reflects the predisposition of the building stock to damage, the damage index represents the **actual response of the built environment** under a given hazard scenario.

Damage expresses the physical consequences of the seismic action on buildings and is described through discrete **damage levels**, ranging from the absence of damage to total collapse. These damage levels represent the outcome of the interaction between seismic hazard, building vulnerability, and exposure characteristics, and therefore constitute an event-dependent measure rather than an intrinsic property of the buildings.

The main objective of the damage index is not to provide a direct quantitative estimate of economic losses, but rather to enable a **qualitative and visual comparison of damage severity** across different portions of the territory. This allows the rapid identification of areas where the most severe effects are concentrated and where post-event impacts are expected to be higher, thus supporting the spatial interpretation of damage patterns.

The index is calculated at the **territorial cell scale**, consistently with the spatial framework adopted in the hazard and risk analysis models. For each cell, the index combines:

- the number of buildings affected by each damage level;
- a weight associated with each damage level, representative of its relative severity.

Operationally, the damage index is defined as the sum of the products between the number of buildings reaching each damage level and the weight assigned to that level, normalized with respect to a worst-case reference condition. The weights are defined within the interval **[0, 1]**, where the lower bound corresponds to the absence of damage (**D0**) and the upper bound corresponds to total collapse (**D5**).

In mathematical form, the index can be expressed as in Equation 4:

$$I_D = \frac{\sum_{i=0}^{5} N_i \cdot w_i}{N_{\max}} \tag{4}$$

where:

- $N_i$ represents the number of buildings within the cell that have reached damage level $D_i$,
- $w_i$ is the weight associated with damage level $D_i$,
- $N_{\max}$ is the number of buildings in the most populated cell of the study area (in the denominator, the worst-case scenario is assumed, corresponding to the condition in which all buildings in the most populated cell experience total collapse D5).

Within this framework, the damage index represents a **relative measure**, useful for ranking territorial cells according to the severity of observed or expected damage. Cells characterized by a high concentration of buildings reaching higher damage levels will exhibit larger index values, indicating greater relative impact with respect to other areas affected by the same seismic event.

A key feature of the damage index is its **event-specific and comparative nature**: under the same seismic scenario, variations in index values reflect exclusively differences in the spatial distribution and severity of damage. This enables an immediate and intuitive interpretation of damage maps, supporting both post-event assessment activities and the prioritization of emergency response and recovery actions.

Finally, the damage index is conceived as a **flexible and scalable tool**, applicable to different territorial contexts and levels of data detail. It does not replace detailed damage assessments at the building scale, but rather provides a synthetic representation of damage patterns, functional to spatial analyses and comparisons among different seismic scenarios.

### 4.3.2 Direct cost index

The **direct cost index** is defined following the same conceptual framework adopted for the vulnerability and damage indices and is conceived as a synthetic measure aimed at representing the **relative spatial distribution of direct economic losses** resulting from a seismic event.

For each damage level $D_i$, a **restoration cost** is associated, representing the cost required to repair or reconstruct the building to restore its pre-event functionality. The maximum restoration cost is, by definition, associated with **total collapse (D5)**, which corresponds to full reconstruction.

Having defined a restoration cost for each damage level, a **cost weight** is associated with each level as the ratio between the cost corresponding to the generic damage level $D_i$and the cost associated with total collapse $D5$. As a result, the weights vary within the interval **[0, 1]**, where 0 corresponds to the absence of damage (D0) and 1 corresponds to total collapse (D5).

The direct cost index is computed at the **territorial cell scale**, consistently with the spatial framework adopted in the hazard and risk analyses. Operationally, the index is defined as the sum of the products between the number of buildings experiencing damage level $D_i$ and the weight associated with that damage level, normalized with respect to a worst-case reference condition.

In mathematical form, the index can be expressed as in Equation (5):

$$I_C = \frac{\sum_{i=0}^{5} N_i \cdot s_i \cdot w_i^C}{N_{\max} \cdot s} \tag{5}$$

where:

- $N_i$ represents the number of buildings within the cell that have reached damage level $D_i$,
- $s_i$ represent the total area associated with the buildings with damage level $D_i$,
- $w_i^C$ is the cost weight associated with damage level $D_i$, defined as the ratio between the restoration cost corresponding to $D_i$ and the restoration cost associated with total collapse $D5$,
- $N_{\max}$ is the number of buildings in the most populated cell of the study area,
- s is the total area associated with the buildings in the most populated cell of the study area.

Within this framework, the direct cost index represents a **relative and dimensionless measure**, useful for ranking territorial cells according to their potential contribution to overall direct economic losses. Cells characterized by a high concentration of buildings affected by severe damage levels will exhibit larger index values, indicating greater relative economic impact under the same seismic event.

As for the damage index, the comparative nature of the direct cost index allows an immediate interpretation of thematic maps and supports the identification of areas where **direct losses are expected to be more significant**, providing useful information for post-event assessment and recovery planning.

Finally, the direct cost index does not aim to replace detailed cost estimates expressed in absolute monetary terms but rather provides a **synthetic representation of the spatial distribution of direct costs**, facilitating comparisons among different areas and seismic scenarios within a consistent analytical framework.

### 4.3.3 Total cost index

The **total cost index** is defined as a synthetic indicator aimed at representing the **relative spatial distribution of overall economic costs** at the territorial cell scale. For each cell, total costs are computed as the sum of all cost components associated with the buildings located within the cell.

Specifically, for the *i*-th cell, total costs include:

- the **mitigation costs**, given by the sum of all pre-seismic intervention costs applied to the buildings within the cell;
- the **direct post-seismic costs**, estimated on the basis of the risk analysis for the buildings within the cell and **discounted to present value**;
- the **indirect costs**, calculated as a fixed **percentage of the direct costs**.

Once the total cost has been computed for each cell, the cell characterized by the **maximum total expenditure** is identified and used as a reference for normalization. The **total cost index** is then defined as the ratio between the total cost associated with the *i*-th cell and the maximum total cost observed among all cells.

In mathematical form, the index can be expressed as in Equation (6):

$$I_{C,\mathrm{tot}}^{(i)} = \frac{C_{\mathrm{mit}}^{(i)} + (C_{\mathrm{dir}}^{(i)} + C_{\mathrm{ind}}^{(i)})_{\mathrm{today}}}{\max_j \left[C_{\mathrm{mit}}^{(j)} + (C_{\mathrm{dir}}^{(j)} + C_{\mathrm{ind}}^{(j)})_{\mathrm{today}}\right]} \tag{6}$$

where

- $C_{\mathrm{mit}}^{(i)}$represents the mitigation costs for cell *i*,
- $C_{\mathrm{dir}}^{(i)}$and $C_{\mathrm{ind}}^{(i)}$are the direct and indirect post-seismic costs associated with the same cell,

The denominator corresponds to the **worst-case cell**, i.e. the one with the highest total cost. Within this framework, the total cost index provides a **dimensionless and relative measure**, allowing the ranking of territorial cells according to their overall economic burden. Higher index values identify areas where the combination of mitigation investments and expected post-seismic losses is more critical, supporting the **prioritisation of interventions** and the comparison of alternative mitigation strategies.

## 4.4 Case study: Campi Flegrei

This section presents the application of the proposed **mitigation analysis framework** to the **Campi Flegrei area**, for which a detailed **building-by-building database** is available. This dataset allowed the definition of the **exposure model** described in Section #, providing a high level of detail in the spatial representation of the built environment.

Building **vulnerability** was characterized using **DPMs**, derived from the study presented (Zuccaro et al 2021). These matrices describe the probabilistic relationship between seismic intensity and damage levels for different building typologies and constitute the basis for the estimation of expected damage under seismic loading.

The definition of **seismic hazard** was addressed with the specific aim of supporting, in the subsequent phases, the identification of the most convenient mitigation interventions. For this reason, rather than constructing a single deterministic damage scenario, the analysis was developed within a **risk-based framework**, evaluating the potential impacts associated with different **return periods**. This approach allows the investigation of how damage distribution varies as a function of the expected seismic intensity and enables the assessment of mitigation effectiveness in terms of future risk reduction.

About **seismic hazard**, to provide a complete picture consistent with the probabilistic approach adopted, all cases associated with the **probabilities of exceedance estimated by INGV over a 50-year time horizon** for the study area are considered. These values were subsequently converted into **macroseismic intensity (IMCS)** using the empirical relationship proposed by **Margottini**, to ensure consistency with the damage probability matrices adopted in the analysis.

The integration of **IMCS**, **DPMs**, and the spatial distribution of buildings by **vulnerability class** allowed the estimation of the **expected damage under the current conditions**. Expected damage is evaluated by considering the distribution of buildings across the six damage levels defined by the **EMS-98 scale** (Grunthal 1998).

Based on this distribution, it is also possible to estimate the **number of collapsed buildings**, obtained by summing the buildings falling within damage classes **D4 and D5**, as well as the **number of unusable buildings**, calculated as the total number of collapsed buildings plus **60% of the buildings classified as D3** damage.

| probability of exceeding 50 years | return period | PGA | PGA mean | IMCS |
|---|---|---|---|---|
| 81% | 30 | 0.025 - 0.050 | 0.04 | 5 |
| 63% | 50 | 0.050 - 0.075 | 0.06 | 6 |
| 50% | 72 | 0.050 - 0.075 | 0.06 | 6 |
| 39% | 101 | 0.075 - 0.100 | 0.09 | 6 |
| 30% | 140 | 0.075 - 0.100 | 0.09 | 6 |
| 22% | 201 | 0.100 - 0.125 | 0.11 | 7 |
| 10% | 475 | 0.150 - 0.175 | 0.16 | 8 |
| 5% | 975 | 0.200 - 0.225 | 0.21 | 8 |
| 2% | 2475 | 0.275 - 0.300 | 0.29 | 9 |

**Table 1.** hazard values in Phlegrean area with respect to different probability of exceeding in 50 years

### 4.4.1 Mitigation strategies

Mitigation is structured into **three consecutive phases**, each involving specific interventions applied to a predefined subset of buildings. After each phase, the distribution of buildings among vulnerability classes is updated, allowing the identification of the new set of structures to be addressed and the definition of the subsequent mitigation step. The adopted approach is based on two main criteria:

1. **Selection of buildings** prioritizing those belonging to the most vulnerable classes (A and B), to maximize overall benefits;
2. **Selection of intervention types**, limited to building features that can be realistically modified through feasible interventions on existing structures.

The updated distributions allow the recalculation of expected impacts for different **PGA/IMCS** values, enabling a quantitative assessment of the effectiveness of the mitigation measures as they are progressively implemented. The following sections describe the three mitigation phases in detail.

#### *4.4.1.1 Phase 1 – Restoration of material capacity*

The first mitigation phase focuses on buildings characterized by **severely deteriorated or aged structural materials**, with the aim of restoring their original mechanical capacity. The intervention targets buildings with **SPD > 1.70** (corresponding to **vulnerability classes A and B**) and construction age belonging to **classes A (before 1919), B (1919-1945), or C (1945-1961)**, for which a significant reduction in vulnerability can reasonably be expected through targeted restoration measures. In this phase, the construction age is shifted to **class E (1972-1981)**, rather than **class F (after 1981)**, to avoid assigning post-1980 seismic design criteria that would imply not only improved materials but also a fundamentally different geometric and structural concept. Such an assumption would not be consistent with the proposed interventions, which aim to enhance building performance without substantially altering the original configuration.

The interventions considered include, indicatively, **local strengthening of degraded masonry**, **repair of damaged portions**, and **improvement of mechanical properties** through surface treatments or injection techniques.

#### *4.4.1.2 Phase 2 – Installation of tie rods*

The second mitigation phase addresses the **installation of tie rods** in buildings where they are absent or ineffective. The intervention is applied to buildings with **SPD > 1.70** (vulnerability **classes A and B**) characterized by **non-rigid horizontal diaphragms** and lacking effective tie rods, i.e. conditions in which this element plays a crucial role in vulnerability reduction.

Tie rod installation represents a key measure for improving the **out-of-plane behavior of masonry walls**, ensuring more effective connections between orthogonal wall panels and significantly reducing the risk of overturning and local collapse mechanisms. As in the previous phase, the intervention focuses on the most vulnerable classes (A and B), where the introduction of tie rods can produce a substantial improvement in overall structural behavior.

#### *4.4.1.3 Phase 3 – Structural strengthening*

The third mitigation phase includes **more significant structural strengthening measures**, applied to buildings with **SPD > 1.85** belonging to **class A** and to a selected subset of **class B** buildings, where residual vulnerability remains critical and the **vertical typology is classified as weak and irregular masonry (V1) or middle quality masonry (V2)**. In this phase, a more intensive mitigation level is adopted, aimed at achieving a substantial improvement in structural behavior. For each affected building, a shift to the **next vertical typology class** is assumed, representing the overall effect of the strengthening interventions.

The measures considered in this phase include **global improvement of the masonry box behavior**, extensive structural strengthening, widespread interventions on connections, and, where compatible, **diaphragm stiffening**. Due to their higher cost compared to previous phases, Phase 3 represents the **maximum mitigation level** considered in this study.

### 4.4.2 Expected impacts for the different mitigation phases

For each of the three proposed mitigation phases, and the resulting distributions across vulnerability classes, the **updated expected impact** was estimated. The aim is to assess how changes in the vulnerability class distribution translate into a **reduction of expected effects** following a seismic event, assuming a **uniform hazard field** over the study area and varying as a function of the considered **return period**. **Table 2** summarises the distribution of buildings across vulnerability classes for each mitigation phase.

| CLASS | Buildings distribution on vulnerability classes | | | |
|---|---|---|---|---|
| | Level 0 | Level 1 | Level 2 | Level 3 |
| A | 1161 | 544 | 246 | 6 |
| B | 2753 | 3255 | 3423 | 2590 |
| C | 840 | 955 | 1085 | 2145 |
| D | 3375 | 3375 | 3375 | 3388 |

**Table 2.** Buildings distribution on vulnerability classes for each mitigation phase

## 4.4.3 Costs analyses

The economic analysis aims to compare the **costs required for each mitigation phase** with the **restoration costs associated with the expected impacts** under the different seismic scenarios considered. This comparison allows the identification of the **most cost-effective mitigation strategy**.

### *4.4.3.1 Mitigation costs by phase*

Each of the three mitigation phases is associated with a **unit cost** derived from average values reported in the literature and related to the planned interventions:

- **Phase 1 – Restoration of material capacity**: includes light masonry strengthening and local connection improvements. Costs are estimated as a function of building surface and construction age and applied to **classes A and B [150 €/m²]**.
- **Phase 2 – Installation of tie rods**: involves the installation of horizontal tie rods to improve out-of-plane behaviour. Costs are calculated for **class A and B buildings** lacking these elements, based on the average number of required tie rods and masonry typology **[100 €/m²]**.
- **Phase 3 – Structural strengthening**: includes more invasive interventions (e.g. jacketing, diffuse strengthening, local stiffening). It is applied to **all class A buildings** and a subset of **class B**, with higher costs estimated from typical seismic upgrading measures **[375 €/m²].**

The total mitigation cost associated with each phase is obtained from the sum of the products of the average costs per square meter and the surfaces of the buildings on which it has been chosen to intervene (available from the database built since collected data). The results obtained are as follows:

- Mitigation cost of Phase 1: **208,121,686 €**
- Mitigation cost of Phase 2: **208,349,286 €**
- Mitigation cost of Phase 3: **624,365,059 €**

### *4.4.3.2 Restoration costs associated with impacts*

Based on the estimated impacts (current conditions and three post-mitigation scenarios), **restoration costs** are computed considering the building's distribution on the level of damages. Adopted unit costs are based on average reconstruction values for masonry and reinforced concrete buildings reported in the literature and adapted to the building typologies of the study area.

| Restoration costs | Level of Damage | | | | |
|---|---|---|---|---|---|
| | D1 | D2 | D3 | D4 | D5 |
| €/m² | € 360 | € 458 | € 545 | € 1,235 | € 1,250 |

**Table 3.** Associated costs [m$^2$] for each level of damage

This approach allows a direct comparison of the effectiveness of the different mitigation strategies, making it possible to identify the most advantageous solutions both in terms of economic efficiency and risk reduction for the building stock.

| IMCS | Total costs analysis | | | |
|---|---|---|---|---|
| | Level 0 | Level 1 | Level 2 | Level 3 |
| 5 | € 148,583,304 | € 323,130,249 | € 229,199,903 | € 626,669,339 |
| 6 | € 277,459,948 | € 384,210,062 | € 276,398,771 | € 640,802,140 |
| 7 | € 387,549,678 | € 403,887,869 | € 311,390,872 | € 664,133,765 |
| 8 | € 476,071,009 | € 421,476,329 | € 331,112,755 | € 679,310,802 |
| 9 | € 564,444,757 | € 428,108,753 | € 355,235,872 | € 700,734,526 |

**Table 4.** Total costs (mitigation + restoration) associated with each level of mitigation and each level of macroseismic intensity

The results clearly show a progressive reduction in expected impacts as mitigation advances. For example, at IMCS 8, the number of unusable buildings decreases from 768 under current conditions to 282 after Phase 3, while collapsed buildings reduce from 341 to 63. A similar trend is observed for higher intensities, confirming the cumulative effectiveness of the proposed interventions.

From an economic perspective, mitigation and restoration costs were combined to assess the overall financial implications of each strategy. Phase 1 and Phase 2 involve comparable investment levels (approximately €208 million), while Phase 3 requires a substantially higher expenditure (approximately €624 million), reflecting the more invasive strengthening measures adopted.

| IMCS | Unusable buildings | | | |
|---|---|---|---|---|
| | Level 0 | Level 1 | Level 2 | Level 3 |
| 5 | 22 | 16 | 13 | 9 |
| 6 | 152 | 122 | 108 | 88 |
| 7 | 475 | 345 | 279 | 193 |
| 8 | 768 | 537 | 421 | 282 |
| 9 | 1077 | 795 | 652 | 460 |

**Table 5.** Estimated uninhabitable buildings for each level of mitigation and at each level of macroseismic intensity

| IMCS | Collapsed buildings | | | |
|---|---|---|---|---|
| | Level 0 | Level 1 | Level 2 | Level 3 |
| 5 | 2 | 1 | 1 | 1 |
| 6 | 28 | 20 | 17 | 12 |
| 7 | 160 | 99 | 70 | 37 |
| 8 | 341 | 201 | 132 | 63 |
| 9 | 540 | 335 | 234 | 125 |

**Table 6.** Collapsed buildings estimated for each mitigation level and at each level of macroseismic intensity

When mitigation costs are combined with restoration costs associated with the expected impacts, the comparison highlights a non-linear behaviour. For lower intensity levels (IMCS 5–6), the current condition (Level 0) is associated with the lowest total cost, as expected damage remains limited. However, as seismic intensity increases, mitigation becomes progressively more advantageous. At IMCS 8 and 9, intermediate mitigation levels (particularly Phase 2) provide a more favourable balance between investment and reduction of expected losses, while Phase 3, despite achieving the greatest reduction in damage, does not always correspond to the most economically efficient solution due to its significantly higher upfront cost.

This behaviour confirms that the optimal mitigation level depends on the hazard intensity considered and on the adopted planning horizon. The application to the Campi Flegrei area demonstrates how the proposed framework supports informed decision-making by:

- quantifying the reduction in physical impacts (collapsed and unusable buildings);
- translating damage reduction into economic terms;
- identifying the mitigation phase that ensures the most effective trade-off between investment and expected loss reduction.

Overall, the case study highlights the importance of integrating probabilistic hazard scenarios, vulnerability evolution, and economic evaluation within a unified analytical structure. The proposed approach does not merely estimate costs but provides a comparative tool to guide prioritization strategies in complex urban contexts exposed to seismic risk.

# 5 Integration of Climate Change within the Mitigation Framework

The mitigation framework originally developed in this deliverable for seismic risk reduction is here extended to explicitly incorporate the effects of climate change. In a non-stationary environmental context, hazard conditions cannot be assumed constant over time. Rising temperatures, increasing frequency of heatwaves, and intensification of extreme rainfall events progressively modify the stress conditions affecting buildings, infrastructures, and open spaces.

Under these evolving dynamics, mitigation strategies must go beyond the reduction of structural vulnerability to geophysical hazards. They must also strengthen the adaptive capacity of the urban system under future climatic pressures. Climate change is therefore treated not as an additional isolated hazard, but as a structural driver influencing how mitigation measures are conceived, dimensioned, and evaluated over the long term.

At the building scale, mitigation measures are designed to simultaneously enhance structural safety and environmental performance. Structural upgrading interventions—such as local strengthening of masonry, slab reinforcement, confinement systems, and roof improvements—contribute to reducing vulnerability to seismic and volcanic actions. These measures improve mechanical capacity and reduce the probability of severe damage or collapse under geophysical stress.

At the same time, energy retrofitting actions—including façade upgrading, insulation systems, roof reconfiguration, and photovoltaic integration—improve thermal performance and reduce energy demand under increasingly intense heat conditions. Particular attention is given to the technical compatibility between structural and energy interventions. Materials and solutions are selected to ensure adequate fire resistance, durability under thermal stress, and mechanical performance under ash load or seismic excitation. In this way, the building envelope becomes both a structural and climatic interface, capable of contributing to multi-risk resilience.

Urban open spaces are reinterpreted as active components of the mitigation framework. Rather than being treated solely as environmental amenities, they are conceived as multifunctional systems capable of supporting both climate adaptation and emergency management functions.

Nature-based solutions, permeable pavements, vegetated corridors, and shaded areas reduce surface temperatures and enhance stormwater infiltration, mitigating the effects of heatwaves and pluvial flooding. Simultaneously, these redesigned spaces improve accessibility, visibility, and spatial continuity, enabling their use as evacuation routes, gathering areas, or safety buffers during seismic or volcanic emergencies. The integration of everyday environmental performance with crisis functionality ensures that open-space interventions generate continuous benefits while strengthening emergency preparedness.

The distinction between ex-ante and ex-post conditions reflects the transformation induced by integrated mitigation measures. In the ex-ante scenario, impacts are evaluated under projected climatic stress and existing vulnerability conditions. In the ex-post scenario, hazard intensity remains externally defined, but its translation into physical and economic impact is altered by improved structural behavior, enhanced environmental performance, and reconfigured exposure patterns.

Mitigation therefore primarily acts on vulnerability and exposure. While it does not modify the magnitude of climatic or geophysical hazards, it changes the way these hazards affect the urban system, reducing expected losses and increasing functional continuity.

To ensure long-term effectiveness, mitigation measures must be dimensioned considering projected climatic trends. Increasing thermal loads and higher rainfall intensities may progressively alter performance thresholds of buildings and urban infrastructures. For this reason, interventions are evaluated not only under current conditions but also under future stress scenarios, ensuring that their protective capacity remains adequate over the planning horizon.

Through this climate-aware perspective, the mitigation framework evolves from a hazard-specific upgrading approach to an integrated multi-risk resilience strategy. Structural strengthening, energy efficiency improvements, and environmental redesign operate together, generating co-benefits across climatic and geophysical domains and supporting the sustainable transformation of vulnerable urban contexts.

## 5.1 Application of the Integrated Mitigation Framework: Focus on the Bagnoli District

### 5.1.1 Urban Context and Multi-Risk Profile

The integrated mitigation framework is applied to the Bagnoli district, located in the western sector of Naples and included within the Campi Flegrei volcanic area. Bagnoli represents a particularly suitable pilot case due to the coexistence of climatic and geophysical hazards within a compact and heterogeneous urban fabric.

The district is exposed to seismic hazard and volcanic phenomena, including ash fall scenarios associated with the Campi Flegrei system. At the same time, it is affected by significant urban heat island effects and localized pluvial flooding, due to high soil sealing, reduced permeability, and morphological conditions favoring surface runoff accumulation.

The presence of former industrial areas undergoing regeneration further amplifies the strategic relevance of the case study, as ongoing urban transformations offer an opportunity to integrate structural upgrading, climate adaptation, and environmental redesign within a coherent resilience-oriented framework.

### 5.1.2 Ex-Ante Multi-Risk Baseline

The ex-ante scenario describes the current vulnerability configuration under projected climatic stress conditions. From a climatic perspective, heatwave impacts are evaluated through estimated hospitalization costs associated with extreme thermal stress events (e.g., 3-day event with peak temperature of approximately 39°C). Higher impact values are spatially concentrated in areas characterized by limited vegetation cover and high building density. Energy consumption per square meter highlights elevated cooling demand in older and poorly insulated buildings, confirming their increased sensitivity to extreme heat. Pluvial flooding impacts, simulated under a rainfall event of approximately 165 mm over three days (with peak intensity around 30 mm/h), reveal localized economic losses linked to structural damage and road restoration costs. These impacts are concentrated in zones with reduced infiltration capacity and high impervious surface ratios.

From a geophysical standpoint, seismic simulations indicate a measurable number of collapsed and severely damaged buildings under moderate events, with corresponding displacement of residents.

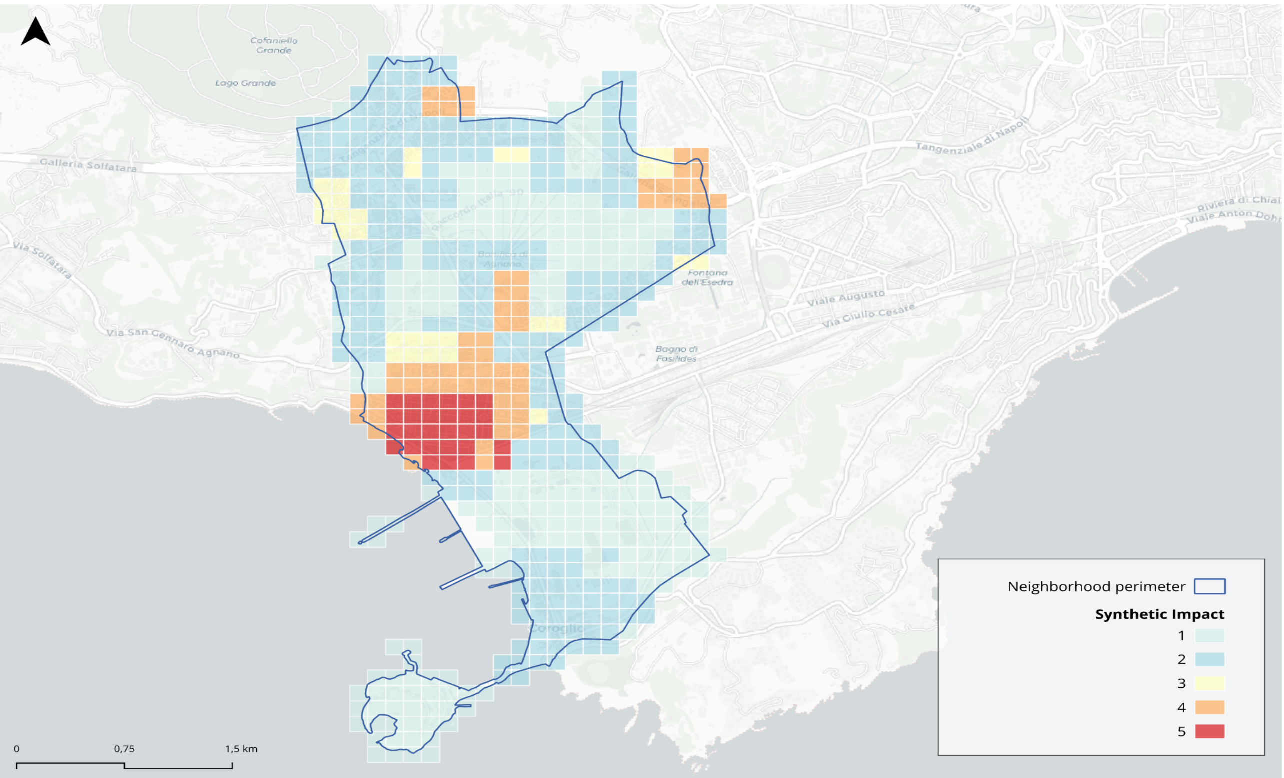

**Figure 1.** Synthetic impact map of the ex-ante scenario for the Bagnoli district. This map provides an integrated assessment of climatic and geophysical impacts at the urban scale, highlighting the most exposed and vulnerable elements under current conditions. It combines estimates of healthcare costs from heatwaves, economic losses from pluvial flooding, and expected building damage and displacement resulting from seismic and volcanic events, offering a comprehensive overview to support prioritization of multi-risk interventions and climate-resilient urban planning

Volcanic ashfall scenarios show potential roof failures in vulnerable building typologies lacking adequate load-bearing capacity.

The integration of these components within the Synthetic Index reveals spatial clusters of elevated multi-risk conditions, where structural fragility overlaps with climatic exposure.

### 5.1.3 Ex-Post Scenario and Quantitative Effects of Mitigation

The ex-post scenario assumes the implementation of integrated mitigation measures acting simultaneously on buildings and open spaces.

At the building level, structural strengthening, roof upgrading, and façade improvements reduce seismic and volcanic vulnerability. Simulations indicate a significant reduction in expected collapsed buildings under the same seismic event, with decreases on the order of several tens of percent compared to baseline conditions. The number of displaced residents shows a comparable downward trend.

Under ash fall scenarios, roof reinforcement and structural upgrading substantially lower expected roof failures, particularly in masonry typologies previously classified as highly vulnerable.

Energy retrofitting measures and improved building envelopes produce measurable reductions in annual energy consumption per square meter, resulting in decreased exposure to indoor overheating during extreme heat events. These improvements are reflected in lower estimated hospitalization costs in the most thermally critical zones.

Open-space interventions — including permeable pavements, vegetated areas, and green infrastructure — increase infiltration capacity and reduce runoff coefficients. Under the same rainfall scenario adopted in the ex-ante assessment, the spatial extent and intensity of flooding-related economic losses decrease in areas where permeability has been enhanced.

Overall, while hazard intensity remains unchanged, modifications in vulnerability and exposure patterns generate consistent reductions in expected impacts across climatic and geophysical domains.

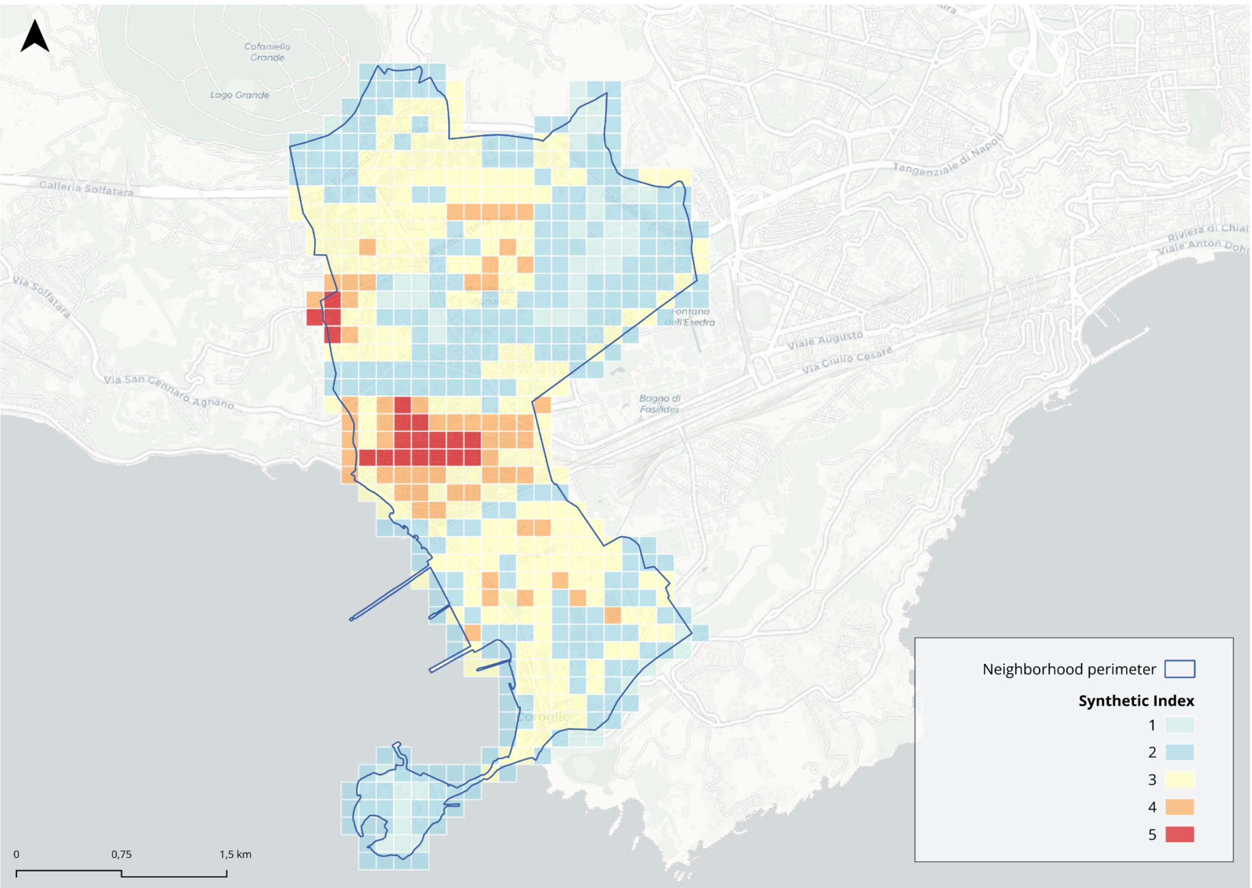

**Figure 2.** Ex-post Synthetic Index of multi-risk conditions in Bagnoli. The index combines updated climate hazard and geophysical impact indicators, reflecting the effects of implemented interventions on buildings and open spaces

### 5.1.4 Integrated Performance and Synthetic Index Reduction

The recalculation of the Synthetic Index under ex-post conditions confirms a spatially coherent reduction in multi-risk levels across the district.

The most pronounced improvements are observed in areas where structural upgrading overlaps with environmental redesign, demonstrating that coordinated interventions produce greater benefits than sectoral measures implemented independently.

The Bagnoli focus therefore confirms that climate-aware structural mitigation and open-space adaptation can operate synergistically, generating cumulative benefits across multiple hazard domains and enhancing long-term urban resilience.

# 6 Conclusions

The study demonstrates the value of integrating probabilistic seismic hazard assessment, vulnerability modelling, and economic analysis within a unified decision-support framework. By adopting multiple hazard intensities rather than a single deterministic scenario, the approach captures the variability of expected impacts over different return periods and supports long-term mitigation planning.

Results for the Campi Flegrei area show a clear reduction in collapsed and unusable buildings as mitigation progresses . However, the economic analysis highlights a non-linear relationship between investment and benefit. While the most invasive strengthening measures achieve the largest damage reduction, they are not always the most economically efficient option. Intermediate measures—such as the installation of tie rods—often represent the optimal compromise between upfront cost and reduction of expected losses, especially for higher seismic intensities.

The introduction of synthetic damage and cost indices enhances the spatial interpretation of results and supports prioritization at the territorial cell scale. Overall, the framework provides a transparent and adaptable methodology that links structural vulnerability reduction to economic performance, enabling informed decision-making in seismic-prone urban areas.

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