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A methodology for the assessment of the integrated vulnerability of Italian residential buildings with respect to seismic risk, flood risk and energy efficiency

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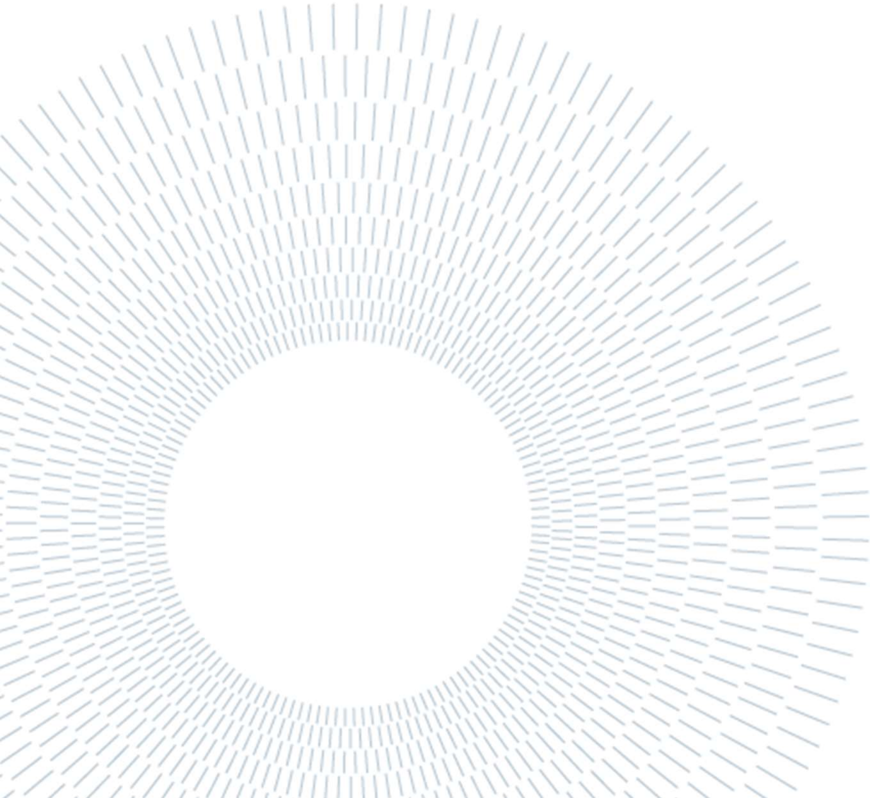

Abstract

In this thesis project, we developed a methodology for the assessment of the integrated vulnerability of buildings. The reasons at the base of the research work were multiple. On the one hand, it is the raising need for a comprehensive understanding of how different hazards affect the built heritage; on the other hand, the absence of a normative body on this subject arises.

The developed methodology considers seismic and flood risk, and energy efficiency and was designed for Italian residential buildings in masonry or reinforced concrete; still, the methodology is flexible and adaptable to other hazards/geopolitical contexts as well as types of buildings. Its implementation to two case studies (Varese and Bergamo) shows that it supports the decision-making process regarding the renovation and/or the new design of buildings, allowing to minimize the total vulnerability of the structure, avoiding negative interactions of interventions (i.e., the adoption of interventions that are good with respect to one risk, but harmful with respect to another one) and, at the same time, optimizing the costs. Accordingly, the outcomes of the work can provide a solid basis for the institution of guidelines or regulations regarding measures for integrated risk reduction. In fact, the presence of a strict normative concerning some risks and the absence of a normative for other risks can cause to disregard the risks not considered by the building codes, which, in its turn, can lead to an overall increase in the integrated vulnerability of a structure. Also, if the methodology is applied at a larger scale, it can support the identification of priorities of intervention (i.e. which buildings are more vulnerable and why).

Key-words: multi-risk, energy efficiency, natural risks, integrated vulnerability, vulnerability assessment

Abstract in italiano

In questo progetto di tesi abbiamo sviluppato una metodologia per la valutazione della vulnerabilità integrata degli edifici. Le ragioni alla base del lavoro di ricerca sono diverse. Da un lato, la crescente necessità di una comprensione globale di come i diversi rischi influenzino il patrimonio edilizio; dall'altro, l'assenza di un corpo normativo in materia.

La metodologia sviluppata considera il rischio sismico e alluvionale e l'efficienza energetica ed è stata progettata per gli edifici residenziali italiani in muratura o in cemento armato; tuttavia, la metodologia è flessibile e adattabile ad altri rischi/contesti geopolitici e tipologie di edifici. La sua applicazione a due casi di studio (Varese e Bergamo) dimostra che essa supporta il processo decisionale relativo alla ristrutturazione e/o alla nuova progettazione degli edifici, consentendo di minimizzare la vulnerabilità totale della struttura, evitando interazioni negative degli interventi (cioè l'adozione di interventi validi rispetto a un rischio, ma dannosi rispetto a un altro) e, allo stesso tempo, ottimizzando i costi. Di conseguenza, i risultati del lavoro possono fornire una solida base per l'istituzione di linee guida o normative relativi alle misure di riduzione integrata dei rischi. Infatti, la presenza di una normativa rigida per alcuni rischi e l'assenza di una normativa per altri rischi può indurre a trascurare i rischi non considerati dalle norme edilizie, il che, a sua volta, può portare a un aumento complessivo della vulnerabilità integrata di una struttura. Inoltre, se la metodologia viene applicata su scala più ampia, può supportare l'identificazione delle priorità di intervento (cioè quali edifici sono più vulnerabili e perché).

Parole chiave: multirischio, efficienza energetica, rischi naturali, vulnerabilità integrata, valutazione della vulnerabilità

Contents

Introduction

The issue of sustainability and the need to find new ways to address the increasing number of extreme natural events arose in the last years, both at the international and national level.
These issues can be addressed from different perspectives, among which we will focus on how it's possible to deal with it from the point of view of the built environment, considering that today buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU [1].
On the one hand, the economic crisis and the climate crisis have caused the urge for more efficient buildings, in order to reduce emissions and costs; on the other hand, the increase in extreme natural events, caused by the climate change, has caused that much more buildings are subject to more than one natural risk, and so there is the necessity to evaluate those risks jointly and implement actions which are efficient in a multi-hazard perspective.
Another aspect is that it became clear that renovating existing building (both in terms of structural enhancement toward natural risks and increasing energy efficiency) is a more climate friendly and economically sound choice [2], as opposed to constructing new buildings, and so this approach has been privileged instead of re-constructing new buildings.

Indeed, climate change, which has greatly increased the occurrence of natural events of exceptional intensity, the pandemic, the energy crisis, among others, are all factors that have increased the sensitivity of institutions among the fact that there is the need for a more accurate risk management, which must be able to consider at the same time various risks and different objectives.

Actions have been implemented, acting on various levels, to reduce exposure, to reduce vulnerability, to renovate existing assets and to develop and implement technologies to be included in renovation and land management plans.
It has been realised that preventive planning allows for easier management of the emergency phase, enabling a reduction of damage to property and people, and faster recovery in the post-event phase.

In addition, the competent authorities (such as the national civil protection, the basin authorities, and the European Commission) have been able to experience how implementing maintenance, modernisation and in general reducing systems' vulnerability brings considerable economic benefit in the long term.

From the point of view of natural risks, the Sendai Framework for Disaster Risk Reduction 2015-2030 was the first major agreement of the post-2015 development agenda, which aims at guiding national and global efforts toward an environmentally sustainable human development, and provides Member States with concrete actions to protect development gains from the risk of disaster. It recognises that the State has the primary role to reduce disaster risk but that responsibility should be shared with other stakeholders including local government, the private sector and other stakeholders [3]. In this agreement, the importance of not only safety but also the resilience of communities to natural disasters was emphasised.

In order to understand how to increase resilience of the built environment, one must first have clear in mind which are the steps for an effective risk management.

The four phases of risk management

Since World War II emergency management has focused primarily on preparedness. Often this involved preparing for enemy attack. Community preparedness for all disasters requires identifying resources and expertise in advance, and planning how these can be used in a disaster. However, preparedness is only one phase of emergency management. Current thinking defines four phases of emergency management: mitigation, preparedness, response, and recovery. [4]

The following diagram (Figure i.1) illustrates the four phases of emergency management.

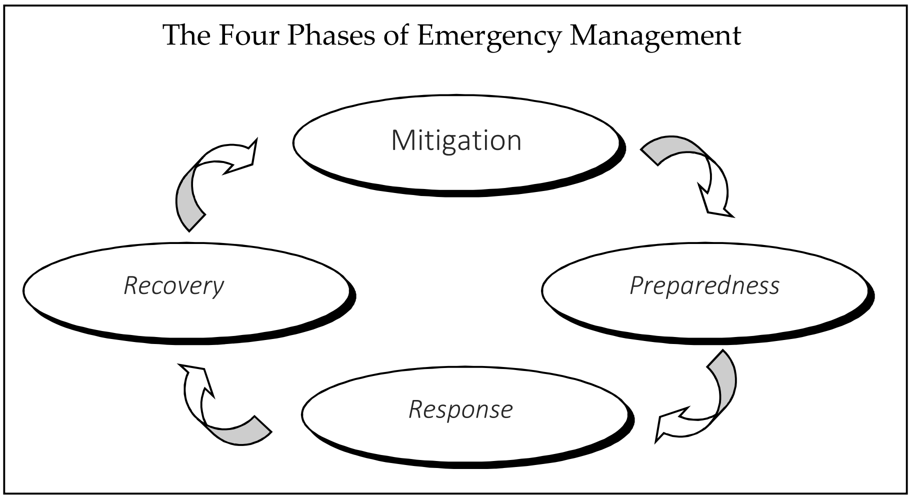

Figure i.1: The four phases of emergency management.

Mitigation

This phase includes any activities that prevent the occurrence of a disaster i.e., reduce the likelihood of occurrence, or reduce the damaging effects of unavoidable hazards. Mitigation activities should be considered long before an emergency. In the time before the event, it is possible to assess all the potential

	risks which the building can face and their intensity. This knowledge permits an efficient design of new structures and also an efficient retrofitting. The assessment should not be performed once, but it should be a process repeated in time, updated with the increasing knowledge that one can acquire, so that retrofitting activities and design rules are always based on the most recent data concerning all the risks that we can expect. [4]
Preparedness	This phase includes developing plans for what to do, where to go, or who to call for help before an event occurs; actions that will improve the chances of successfully dealing with an emergency. For instance, posting emergency telephone numbers, holding disaster drills, and installing smoke detectors are all preparedness measures. [4]
Response	This phase deals with doing all that is possible to manage the emergency in the most efficient way, in order to reduce, as much as possible, the damage. Personal safety and well-being during an emergency depend on how prepared one is and on the ability to respond to a crisis. By being able to act responsibly and safely, one will be able to protect himself, his family, others around. These actions can save lives. If the mitigation and preparedness phases have been managed correctly, during the response it is possible to save the majority of buildings and human lives. [4]
Recovery	After an emergency and once the immediate danger is over, safety and well-being depend on one’s ability to cope with rearranging its life and environment. This is a crucial moment, since at this time we have the possibility to acquire new knowledge about the event that stroke, about how the build environment responded to the event, and we can verify if the retrofitting or building techniques implemented before have been effective or not. At this time, we can gather all past and new information to rebuild or renovate damaged buildings in a better way than before. During recovery, we should also consider things to do that would mitigate the effects of future disasters. [4]

Having this in mind, we can understand better how to increase resilience, understood as the capacity of the structure to absorb a damage and returning to be operative in the shortest time and with better performances.
This can be enhanced acting on different sides:

- we can increase our capability of predicting events, building better structures, which will resist the event when it comes, thus reducing the vulnerability of the structure.

- we can work on exposure, limiting (when possible) the presence of strategic and valuable structures in areas where we expect major events.
- we can define emergency plans, so to limit the consequences of the event.

However, preventive retrofitting of a structure is economically convenient with respect to the costs of repair or reconstruction, and this even if we disregard all the indirect costs caused by the inactivity of the structure, especially if we deal with strategic structures, and this is why preventive retrofitting and accurate design prescriptions are the best tool we have to reduce to the minimum the consequences of a hazardous event.

For what concerns the issue of energy efficiency, it has been strongly addressed in the Sustainable Development Goals (SDGs) 2030 Agenda.
The 2030 Agenda, established in 2015, is an agreement between 195 Nations which, fixing 17 targets for the year 2030, aim at promoting the human development and making it more sustainable.
The 17 targets are referred to a number of aspects of human sustainable development and, among them, goals 7, 11, 12, 13 address specifically the issues of energy efficiency and sustainable development, being respectively:

- 7, Affordable and clean energy;
- 11, Sustainable cities and communities;
- 12, Responsible production and consumption;
- 13, Climate action. [62]

Each target proposes actions and objectives to be achieved by the year 2030, with the aim of ensuring a better world for future generations, and in the 17th target it is clearly stated that this goal cannot be achieved alone, but they must be jointly addressed and that nations must cooperate together to this end. [5]

One of the main concepts highlighted in the 2030 Agenda is that, living in a planet which is undergoing a strong and fast climate change, communities have no choice but adaptation. This means that when we think about cities and communities in general, we must think of them as living being, capable to change and adapt, according to the environment, and forget the idea that we can force the nature to our wills.
To this end, the main tool we have is energy efficiency, and the best option is to reduce significantly the production of energy with fossil fuel, in favour of green and renewable resources.

This would have a series of positive consequences not only in terms of clean energy (target n° 7) but also for targets 11, 12 and 13.

At this point we have understood that:

- when dealing with the problem of multi-risk, the best option is to renovate and prevent;
- when dealing with the issue of energy, making the structure more efficient has important and positive consequences, both from an environmental and social point of view, and also from an economic point of view.

Now, it become clear that, if we want to address together the multi-risk approach towards natural risks and, at the same time, offering a sustainable solution, we must renovate existing buildings (instead of re-building new ones) with actions that can jointly improve safety and energy efficiency.
This multi-risk (among natural risks) and multi-objective (toward natural risks and energy efficiency) approach was proposed, at a European level, in the Renovation Wave.
As part of the European Green Deal, which proposes a package of initiatives aimed at setting the European Union on the path of a green transition to achieve zero carbon footprint by 2050, the Renovation Wave aims to renovate structures, both public and private, as the key to reducing emissions and also as a mean to invest private and public money in the most efficient way.
In addition, a strong push towards retrofitting actions can help to play a crucial role in European economic recovery after the Covid-19 pandemic [63], as well as create new green jobs in the construction sector and improve the quality of life for residents.

Finally, it's noticeable to highlight some previous studies which pioneered multi-risk or multi-objective approaches.

One of them is the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' aimed at increasing the understanding of the main criticalities in terms of seismic vulnerability and energy efficiency for ageing buildings.
The first results of the project, which is still in development, was presented in a report by the Joint Research Centre report in 2020. The objective is to improve stakeholder understanding on critical energy efficiency and seismic safety upgrades to ageing buildings and the interest was not only focused on integrated solutions, but also to the increase of resilience of the build environment. [6]

For what concerns multi-risk, another example is "A PROMETHEE Multiple-Criteria Approach to Combined Seismic and Flood Risk Assessment at a Regional Scale", aimed at proposing a qualitative multi-hazard risk analysis methodology in the case of combined seismic and flood risk using PROMETHEE, a method for evaluating alternatives with respect to criteria in multi-criteria decision-making problems. [7]

Having understood the importance of managing individual risks in the pre-event phase, the fact emerged that actions to implement safety can be thwarted, or even have adverse effects, when there are multiple risks involved.
A clarifying example of this phenomenon is given by constructions on *pilotis*: this type of architectural solution, introduced in Le Corbusier's 'Five Points of Architecture', is extremely effective for buildings subject to flood risk. In this case, in fact, the absence of a ground floor and the development in height of the building makes it possible to keep the inhabitants safe, as well as the structural body itself. On the other hand, however, research in the field of earthquake engineering has shown that the presence of interruptions in the building's continuity in elevation are among the main causes of structural damage or collapse, since they can induce collapse mechanisms such as the developing of "soft storeys".

This phenomenon is repeated for a large number of combined risks, and today the escalation of the intensity and frequency of extreme natural phenomena brings the need to think in a multi-risk perspective.
The question therefore arises: considering that most of the built environment is exposed to more than one risk, how can one choose how to build or how to act on the structure, so as to use the most effective techniques while avoiding conflicting effects?

With the study developed in this thesis, the aim is to provide a tool to answer this question from a multi-hazard and multi-objective perspective.
The basic idea is that risk mitigation, in order to be effective, durable and economical, must be able to implement optimised actions that improve the safety of the building not only with respect to a single risk, but that have an influence on all the significant vulnerabilities. At the same time, such actions should not have contrasting effects in a multi-hazard perspective and must privilege the predominant risk.
The aim is therefore to develop a method to first assess the vulnerability of a building with respect to single risks, and then combine the vulnerabilities together, to understand their scale of priority and then act accordingly, thus understanding what the integrated vulnerability of a building is.

In this study, interest has focused on three topics: flood risk, seismic risk, and energy efficiency.
The latter refers more properly to the possibility of applying energy efficiency techniques. It is not to be understood as a risk, nevertheless is important and must be addressed in the multi-objective approach that we are proposing.

The reason why we choose those risks for the project is that both flood and seismic risk are a major threat in the vast majority of the Italian territory (Chapter 3).

In fact, all the Italian territory is classified as seismic, so each building, infrastructure and so on have to be built or retrofitted based on anti-seismic norms. And in particular, the 44% of the national territory is classified high seismic risk, making 22.2 million people exposed. [8]

For what concerns the risk of flooding, according to the 2021 report from the ISPRA institute (Istituto Superiore Protezione e Ricerca Ambientale), in the period 2012-2018 in Italy we had more than 314 flooding episodes, which are slightly less than one per week.
The phenomenon of flooding includes a vast portion of the national territory, 5,4% in high probability, 10% in medium probability and 14% in low probability. [9]
However, it's possible that a larger portion of the territory is at some level of risk, but this information is unknown since not all the territory is classified.

On the other hand, nowadays it's not possible to conceive a study without considering the energy impact, especially in a country like Italy which is poor in carbon-fossil energy sources and so has a great push toward renewable. In fact, the production of electricity in Italy is still very much dependent on fossil fuels, nevertheless in the last years, the contribution of renewable resources in the Italian energetic mix has constantly grown.
In 2021, renewable sources covered 36% of national demand, with electricity production from photovoltaics and wind power at an all-time high. [10].
If we consider the economic throwback, producing green energy is much more convenient, and this could reduce the costs for the families, and also new green power plants in Italy would create a non-negligible number of new jobs.
Italy has the potential to become 100% renewable by 2050 according to a study conducted by 26 researchers from the Universities of Stanford, Berkeley, Berlin and Aarhus, which has proposed a scenario for the year 2050 when they imagine the energy production to be 100% green. The consequence would be almost 500 000 new jobs and 46000 deaths avoided. Moreover, according to the article, the total transition to wind, hydro and solar energy worldwide would save 22 800 billion dollars a year for pollution effects and 28 500 billion dollars a year for climate effects. [11]

In Italy, the issues of risk prevention, mitigation, assessment and management are very topical, and it is therefore important that the scientific community makes every effort to develop knowledge in these fields. The seismic events in Abruzzo (2009), Marche (2016), Emilia (2012), the flood in Marche (2022), volcanic activity in the Aeolian

Islands (2022), as well as avalanche and landslide phenomena, are just a few examples of how fragile our territory is.
According to the UNDRR, United Nations Office for Disaster Risk Reduction, [3] Italy is one of the European nations most prone to natural disasters; in fact, our country ranks first in terms of seismic, flooding, volcanic and other risks. This natural propensity to risk, which is further accentuated in the Southern area, also induces a greater propensity to technological risks triggered by natural events (Na-tech).

Moreover, in Italy, on a totality of 12187698 residential buildings, 6911180 buildings have been built before 1970, meaning that more than 55% of buildings are more than 50 years old [13]. The building heritage is therefore particularly fragile and needs special attention, in particular because a large portion of old buildings have historical and cultural value.
All this makes Italy the ideal laboratory for the implementation of modern risk management techniques and the application of new techniques aimed at reducing the vulnerability of the built environment (the project Complessi Antisismici Sostenibili ed Ecocompatibili, C.A.S.E L'Aquila [14]).

For what concerns the normative body, many regulations, in particular for buildings, have been provided by the European Union regarding the topic of risk mitigation and regarding how to deal with specific risks, and all these indications have been transposed by member states.

For what concerns the seismic risk and norms of construction, Europe has provided the Eurocodes, 9 codes regarding all the main aspects of structural design and regulations. In particular, Eurocode 8 is devoted to seismic design. Anyway, in Italy we had the presence of regulations regarding seismic risk already before the issuing of the Eurocode in 1998.

Already in 1627 in Campania region, institutions suggested some specific type of constructions ("Case baraccate") for wooden structures, since they were known to perform better under seismic action.
Other regulations followed in the years, providing local solution, as for example the building code issued by the Pope Pio IX in 1859, after the Norcia earthquake.
Many other norms followed, always addressing the problem of seismic risk at a local level and at a time when the event already stroke.
We have to wait the year 1974 for the first national seismic classification of the territory and related building norms.
After the release of the Eurocode in 1998, Italy has followed the European footprints, and developed the Italian Building Code, of which the newest version dates 2018.
In the IBC, based on the 1974 regulation, we can find the same basic concepts as in the

EC, even though the requirements are more strict, due to the high levels of risk in the country.
Previous norms issued at a national level, concerning the classification of the territory in seismic zones, have been updated according to the increased knowledge acquired during the years. The last classification, released in 2003, classifies the entirety of the national territory as seismic, subdividing the seismic zones in 4 classes of decreasing risk.
For what concerns the prevention of seismic events, at a national level, the events that struck central Italy between 2009 and 2018 drew the public's attention to the urgency of defining regulations to reduce risk and make the building heritage safe, understood not only as private structures, but also public buildings, strategic infrastructures and cultural heritage.

In past years, this need for an organic understanding of the building heritage arose every time a particularly intense seismic event occurred.
Yet the problem has never been tackled concretely, due to the large number of subjects involved, the chaotic nature of the procedures, and above all, due to the strong emotional component, caused by the high number of victims, which is characteristic of high-intensity seismic events, and which does not allow for a clear-headed management of the emergency.
Therefore, as we have seen, in Italy there was no precise picture of the state of the art concerning seismic risk prevention activities.
To this end, law no. 77/2009 established the National Plan for the Prevention of Seismic Risk which, together with the fund for seismic risk prevention, establishes the means for reconstruction and seismic risk prevention in Italy.
Furthermore, in 2010, a Commission of seismic risk experts was formed to define the objectives and general criteria for effective prevention action to be implemented with the funds made available.

With respect to the flood risk, the European Union in 2007 has adopted the Floods Directive. This tool provides guidelines for the management of the flood risk, and a combined action at a communitarian level. Moreover, gives indications on how to draw up maps to indicate the extent of risk, flooding area, the exposed elements, as well as providing guidelines for the issuing of plans to reduce the risk.
This directive has been transposed into Italian law with Legislative Decree 49/2010, also considering existing national legislation. Thus, hazard and risk maps have been drawn up for each of the five river district into which the national territory is divided, and Flood Risk Management Plans have been drawn up by the district authorities.
Still it is noticeable the weak of existing regulation regarding the issue of flood risk.
As a matter of facts, in Italy there is not a regulation which defines a proper way to build in an area subject to flood and neither there is a unique national classification of

the territory. The territories of the five major river districts are classified in high, medium or low risk, but for each river district the criteria of classification are different, hence it is not possible to compare the state of risk for the portion of territory classified.

Considering the energy efficiency, the normative body, especially on the behalf of the European Union, is extremely wide and touches a number of different topics. In the following, we provide a list of the most significant norms introduced in the last decade.

- Directive 28-2009 EC on the promotion of the use of energy from renewable sources, establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final energy consumption and for the share of energy from renewable sources in transport.
- Directive 31-2010 CE - EPBD 2° on the energy performance of buildings, with the aim of "promoting the improvement of the energy performance of buildings within the Community, considering outdoor local and climatic conditions, as well as indoor climate and cost-effectiveness requirements".
- Directive 844-2018 UE – EPBD 3° which modifies the directive 2010/31/UE on the energy performance of buildings and the directive 2012/27/UE on energy efficiency.
- Legislative Decree No. 48 of 2020 implemented the 2018/844 EU Energy Performance of Buildings Directive (EPBD [15])
- EU Directive 2001-2018 on the promotion of the use of energy from renewable sources.
- The 20-20-20 target comes into play in Directive 28/2009. By 2020 in the European Union:
    - 20% improvement in energy efficiency
    - 20% reduction in greenhouse gas emissions
    - 20% energy production from renewable resources
- The "Minimum Requirements Decree", which defines the application methods for the calculation of the energy performance of buildings, including the use of renewable sources, as well as the prescriptions and minimum requirements for the energy performance of buildings and building units buildings. [16]
- The Legislative Decree 199/2021 with the aim to accelerate the path of sustainable growth of the country, laying down provisions on energy from renewable sources, consistent with the European objectives of decarbonisation of the energy system by 2030 and complete decarbonisation by 2050. This decree defines the tools, mechanisms, incentives and the institutional, financial and legal framework necessary to achieve the objectives of increasing the share of energy from renewable sources to 2030. This decree lays down provisions necessary for the implementation of the measures of the National Recovery and

Resilience Plan (PNRR [17]) concerning energy from renewable sources such as the updating of the minimum percentages of energy from renewable sources in buildings.

- The Decree on Energy Certification - Legislative Decree 192 of 2005: Legislative Decree 192 of 2005, with its numerous updates over the years, is the fundamental national decree for calculating the energy performance of buildings, for new buildings and for upgrading interventions. This decree is in implementation of European Directive 91 of 2002.

However, at the present state, no national law or regulation deals with the issue of integrated vulnerability. Each regulation addresses specific risks, disregarding the important aspect of the necessary of a multi-risk approach for a correct and efficient risk reduction.

At this point of the discussion, it is necessary to open a parenthesis on the terminology that will be used in this thesis. This clarification is necessary because, although the subject of risk is a topic of great debate at the moment, there is still no unified definition of what a risk is, and what its components are. Risk is defined as the combination of three components: vulnerability, exposure and hazard.

In particular, vulnerability is defined as the susceptibility of a structure to suffer a certain amount of damage under the action of an event of a given intensity. Vulnerability takes on values from 0 to 1. For example, if the characteristic event occurs (may it be an earthquake or a flood) the greater the damage the structure suffers under this action, the greater its vulnerability. Hence the vulnerability is not linked to the event itself, but to the damage level reached by a structure. Under the same action, two structures with different levels of vulnerability can suffer higher or lower damages.

The definition of vulnerability itself explains also why we are interested in the concept of integrated vulnerability. For the sake of risk mitigation, we can act on each of its components separately or jointly. But since we are interested in actions, retrofitting measures or design solutions to be applied on buildings, those goes to reduce the vulnerability of the structure, leaving unaltered the risk components of exposure and hazard.

Risk mitigation is the process of assessment of potential risk, to be understood as the totality of damage, followed by the introduction of countermeasures to minimize the losses suffered by the exposed values, hence reducing the vulnerability. A risk can be approached at each of its stages, as it was made clear when we defined the steps for an effective risk management.

It is clear that the ultimate goal is the reduction of losses in economic terms and in terms of human lives, and this goal cannot be achieved by acting directly on a single phase, but rather with an organic action that focuses on the reduction of vulnerability, on an effective emergency plan, and on a conscious reconstruction aimed at protecting new and existing assets from future events.

Mitigation is therefore the strategy we use when we cannot avoid a threat. Mitigating the risk requires us to take some action that can reduce the severity of the impact should the threat occur.

Having defined the concept of vulnerability, we can take a step further in the definition of integrated vulnerability. We define integrated vulnerability, at a specific location, as the sum of the individual vulnerabilities, weighted together according to the expected annual loss (Chapter 4). We think that dealing with integrated vulnerability is the best approach in order to address completely the issue of risk mitigation.

For the moment, what is important to bear in mind that, when dealing with integrated vulnerability, one must look at the concept of risk in a more complex way, always considering that there are many risks involved, each having its own influences on the total vulnerability of the structure, and that the relationship between those risks depend on both the vulnerability and the damage (in terms of economic loss) that they can produce.

Our objective with this thesis project is first to develop a fast, efficient methodology to assess the integrated vulnerability of buildings with respect to different types of risk. We will choose three classes of risks for Italian residential buildings, but the methodology is conceived so that it can be adapted to other building typologies (commercial buildings, industries, cultural heritage etc…) and to other risk typologies. The second objective is to apply this methodology to real cases, in order to evaluate the integrated vulnerability of existing buildings and suggest some interventions to ameliorate the buildings conditions; to apply the methodology to validate new design projects; and finally, to suggest the application of the methodology as a research tool on a large scale in order to develop national guidelines or regulations addressing the issue of integrated vulnerability and integrates risk mitigation.

1 Methodological approach

In the following chapter, we are going to describe which is the methodological approach proposed for the assessment of the integrated vulnerability. Following, an exhaustive description of the types of vulnerability will be provided, together with an analysis of the state of risk in Italy. Before all, we want to stress the fact that, even though in this thesis project the focus is on three types of risk and the related vulnerabilities (seismic, flood and energy efficiency), the goals are:

- To provide consistent results regarding multi-risks, which can be expanded to the vast majority of residential building, in Italy and abroad, in terms of which actions is better to implement when various risks comes into play. The idea of "better" here is to interpret as most effective for a safety point of view and most convenient in a cost-benefit perspective.
- To understand which is the impact of given characteristics of a structure with respect to different vulnerabilities and consequently to provide meaningful suggestions for efficient retrofitting and maintenance actions. In particular, we expect to find some structural characteristics which can benefit the safety of buildings with respect to all risks, and others which, on the contrary, can be harmful. In the case of opposite effects on safety of a given structural characteristic with reference to different risks, the methodology should be capable of suggesting how to choose the best action to put into play.
- To propose a methodology which can be extended to other types of risks (industrial, landslide, Na-tech, etc), and to other building categories, depending on risks that are most relevant at a given location.

1.1. Types of vulnerability subjected to integrated vulnerability analysis

As previously stated, the classes of vulnerability which will be analysed are: seismic vulnerability, flood vulnerability and energy efficiency. For what concerns the latter, we are aware that the issue of energy efficiency is far by the concept of risk. However, we want to deal with this issue and this is possible since we will measure the risk in terms of economic loss, and the evaluation of monetary loss is possible also in terms of lack of efficient solutions for residential buildings. In fact, we are trying to implement a multi-objective methodology, which considers both the multi-risk and energy efficiency.

The proper way to estimate the seismic safety of a structure is to measure it as the ratio between the Capacity Peak Ground Acceleration (PGA_C) that caused the building to reach the limit state and the Demand Peak Ground Acceleration (PGA_D) of the site where the building is located, with reference to the same limit state. [18]

In fact, in the case of an earthquake, the most hazardous actions are horizontal displacements, for two reasons:

- The theory of elastic wave propagation tells us that slow S-waves induce a displacement in the soil orthogonal to their direction of propagation. We also know that, in general, S-waves arrives vertically to the ground surface, thus inducing horizontal displacement at the base of the structure. Also fast P-waves are present during an earthquake, but they induce vertical displacement which can be more easily resisted by the structure (Figure 1.1).
- Buildings are generally designed to bear vertical actions instead of horizontal ones, hence in the presence of additional horizontal loading a safety verification is required.

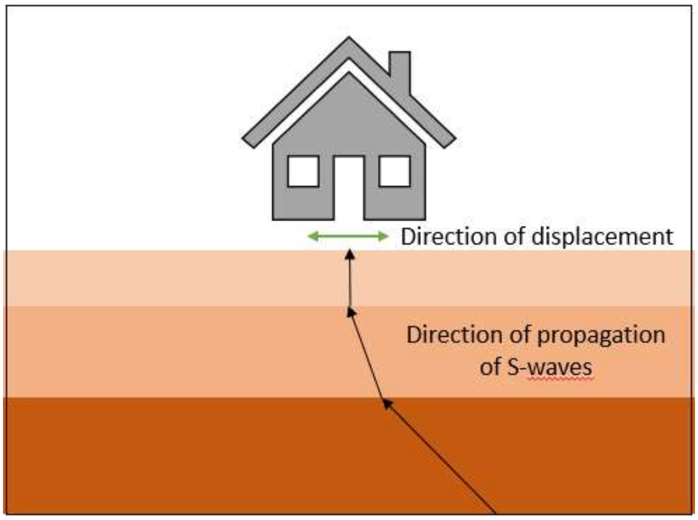

Figure 1.1: Scheme of wave propagation and displacement induced by S-waves

So, in the case of an earthquake, we have firstly vertical displacement, which are bearable by the structure, but still can cause some initial damage with consequent reduction of the structural capacity, and then the building suffers horizontal displacement, and this is the most critical moment when the majority of damages occurs, since the structure is generally weaker with respect to horizontal actions, and in addition the shear action last for a longer time, possibly causing the drop of shear resistance of the structure due to cyclic loading.

In order to evaluate the capacity of a structure, one should perform a complex analysis, requiring a deep knowledge of structural geometry, material properties, etc… and the analysis itself is not straightforward, requiring multiple degree of freedom models (linear static, non-linear static -pushover-, dynamic, etc…) that must be solved via computer codes. It is clear that evaluating the exact capacity of buildings, in order to determine the structural safety, at a large scale is unfeasible. Hence, we have to adopt a different approach which permits less accurate but easier assessment of structural safety or, as we called it, of structural vulnerability.

The alternative we are proposing is to apply qualitative analysis based on a series of factors, which are known affecting the bearing capacity of a structure. Similar simplified qualitative procedures have already been applied. One example are the reports provided by the Italian Department of Civil Protection (schede AeDES [19]) for the evaluation of post-seismic damage.
With this procedure it is not possible to obtain a value of capacity in terms of Peak Ground Acceleration to be compared with the demand, but we can estimate the level of goodness of structural design with respect to seismic actions, and in the context of a large-scale assessment, this is already an important information.

Related to flood risk, the issue of vulnerability must be addressed not only in terms of the possibility of water to penetrate inside the building causing damage to materials, components and plants, but also with reference to bearing capacity with respect to water pressure. In fact, flood effects on building can be distinguished in two classes:

- Effects induced by the presence of water, as the horizontal hydrostatic force, buoyancy, and contamination due to immersion.
- Effects induced by the speed of the current, as the hydrodynamic load, the impact of objects carried by the flood and the undermining of foundations.

When we are in an area where relatively low water levels are expected, we can assume that the best protection for the structure is to make it waterproof. This means avoiding the penetration of water inside the building and designing the exterior in such a way that it’s not (or slightly) damaged by the action of water.
However, when we expect high water levels, keeping all the water outside the building is not the best choice, firstly because it is almost impossible to avoid any seepage through windows, doors, etc… and second because, after a certain height, the external pressure of water (F) overcomes the horizontal bearing capacity of external walls (C) and when this condition is met we have structural failure (Figure 1.2).
That is why, if we expect intense flooding with high water levels, the best choice is to design a guided flooding. Guided flooding means designing a path through which the water can enter the building in a controlled way and without causing damage.

In such a way that the internal areas devoted to flooding will be designed to suffer the minimum damage due to the immersion.

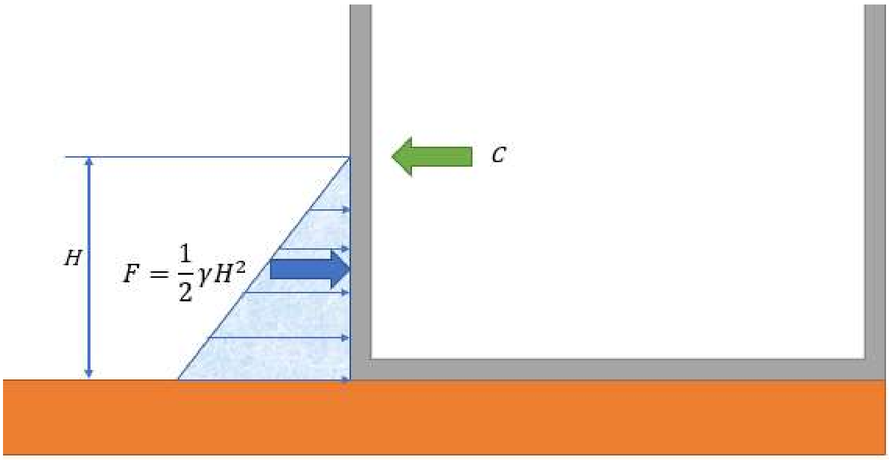

Figure 1.2: Scheme of hydrostatic pressure of water on external walls

In the end, we have to address the issue of energy efficiency. This topic is extremely wide and complex, but here we want to focus on the core concepts.
Energy efficiency aims at reducing the emission of a building. This can be achieved by reducing energy consumption in order to minimize the impact on the environment:

- Firstly, it is related to the reduction of energy demand, which can be achieved by introducing high efficiency materials/solutions to n reduce need of thermal energy for heating/cooling/domestic hot water.
- Secondly, reducing energy consumption implies using highly-efficiency HVAC (Heating, Ventilation and Air Conditioning) and lighting systems and installing renewable resources plants to generate renewable energy on-site.

Summing up, the energetic efficiency of a building is the balance between the energy consumed and the energy transferred to the environment.
The best case scenario is represented by a building which is able to generate its own energy (for example by employing renewable resources such as photovoltaic plans) and do not resituate waste (not only material waste, but also in terms of heating).
The worst case scenario, instead, is the opposite one, in which, in order to be functional, the building must take energy from non-renewable resources and introduce waste of any kind in the environment.
The energy requirement of the structure to be functional in comfort conditions is

therefore the main factor to evaluate the energy efficiency, and can be evaluated through the basic heat balance, considering the losses and the gains. In the following we present the example of heat balance for winter (Figure 1.3). The losses of thermal energy are given by the heat lost by transmission through walls, windows, windows and roofs, and the heat lost by ventilation. The gains are given by the internal heat produced by the appliances. [20]

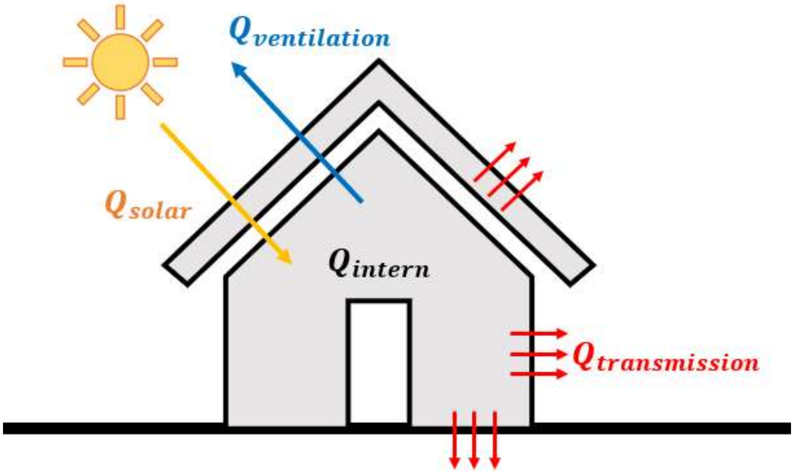

Figure 1.3: Basic heat balance components
Q_{intern} = thermal energy produced inside the building
Q_{solar} = energy gained by the Sun
$Q_{trasmission}$ = thermal energy dispersed in the environment (this transmission has opposite direction in summer or winter seasons)
$Q_{ventilation}$ = additional heat lost due to ventilation

This predisposition of a building to the more or less efficient can be evaluated considering all the characteristics that increase or decrease the efficiency of a structure, more generically the energy efficiency of a building can be expressed through an unambiguous parameter, such as the specific non-renewable primary energy requirement [kWh/m^2], which is the basis of energy retrofit in Italy but also in other countries.

Now that we have defined the classes of vulnerability that we are going to analyse, we want to justify the reason why we choose them, among all the others.

First of all, we want to address the issue of seismic risk. Considering the European context, Italy, together with Turkey, Greece, Albania and Montenegro, are the most hazardous regions of the continent.

This seismicity in the area is caused by a complex tectonic situation, mainly characterized by the collision of the Eurasian plate and the African plate. Focusing of the Italian territory, we can identify three major seismic systems (Figure 1.4):

- The first is the normal faulting (compression) of the African plate (pushing northward) toward the Sicilian plate (pushing southward), causing major seismicity in the area of the Calabrian Arc and major volcanic activity in the zone of the Aeolian islands.
- The second source of major seismicity is given by the normal faulting of the Adriatic plate (which is an extension of the African plate) toward central Europe. This faulting system formed the Alps;
- The last system is the reverse faulting (extension) in central Italy. In fact, the Apennines are formed by the collision between the Adriatic plate and the Eurasian plate. But at the same time the Eurasian plate is moving counter-clockwise toward southwest. This is causing the opening of the territory in the western side of the Apennines and causing the major earthquakes in central Italy of the last years.

Major events have always occurred in the peninsula, and so the natural predisposition of the territory, together with the lack of regulations induced a tremendous amount of economic losses and victims.
In the past, few municipalities, which had been historically hit by major earthquakes, had design regulations based on the practical knowledge.
It was only at the beginning of the XX century that experts started to classify some portions of the national territory on the basis of the knowledge of passed seismic events, but it was only after 2003 the totality on the national territory has been classified as seismic, on the basis of passed earthquakes and evidence of faulting systems.
The issue with classification is that our knowledge is mainly based on a general idea of the tectonic situation at a given location, supported by the evidence of historical earthquakes, and only in a very small number of cases we have the physical evidence of a fault.
Hence there is always the possibility that an area which is classified as slightly seismic could be hit by a modest or large earthquake.

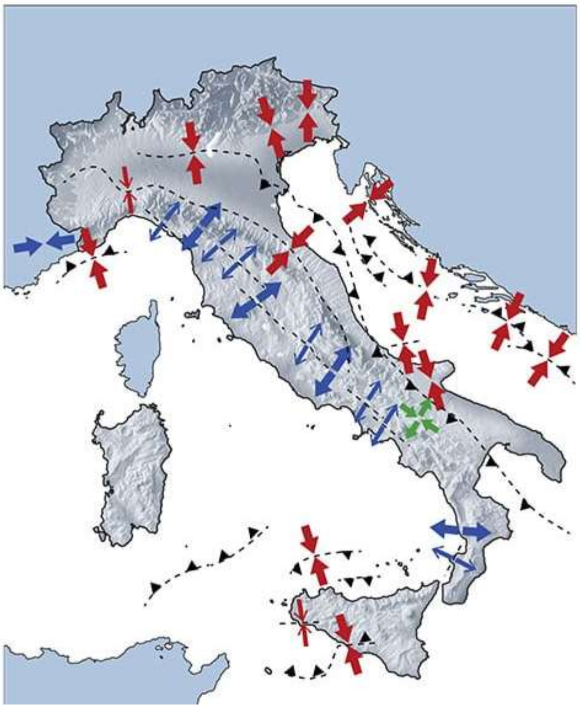

Figure 1.4: Basic seismic systems in Italy

Before 2003 the 63% of municipalities were considered not seismic, meaning that in those regions, all structures built before 2003 are not designed against seismic actions. This problem become extremely relevant if we consider the following: the previous classification, dating back to 1984, considered the vast majority of Northern Italy and Sardinia as not seismic. At the same time, 60% of the built heritage was built before 1980.

This means that there is a large number of buildings are in seismic areas, and not designed to resist horizontal actions. And the situation is even worse is we go more back in time.

It's so clear that there is the urge of an extensive assessment of the situation of the built environment in our country, in order to reduce the possible future losses. In Table 1.1 are shown all the major events occurred in the last century in Italy. [21]

Table 1.1: Seismic events in the last century.

	Magnitude	Year	Victims
Irpinia	6.7	1930	1400
Irpinia	6.2	1962	15
Valle di Belice	6.1	1968	400
Friuli (sequence)	6.4	1976	989
Irpinia	6.9	1980	3000
L'Aquila	5.9	2009	308
Emilia	6.0	2012	26
Umbria-Marche	6.5	2016	300

After, we have to address the issue of flood risk.
In Italy, 93,9% of municipalities are at risk of hydrogeological instability, in a climate situation in which extreme phenomena are in rapid growth: if we consider the years 2021-2022, we have an increase of +19% in floods and inundations [12].
Climate change has induce a rapid growth of every kind of meteorological events, like droughts, windstorm, etc… but focusing on the issue of flood, we can see that in the year 2022 in Italy we had:

- 104 floods due to heavy rainfall;
- 14 damages to infrastructure due to heavy rainfall;
- 4 damages to historical heritage due to heavy rainfall;
- 13 river flooding.

The most affected areas are the ones located in Northern Italy and in particular Lombardy, followed by Lazio and Sicily, while the most affected provinces are Rome, Salerno and Trapani [12].

The origin of the flood hazard is given by the presence of rivers, and not surprisingly the region of the Po plane is one of the most subjected to flood risk, and we can see how the areas subject to flood risk diminish as we move to the South, due to the absence of important waterways.

It's important to recall that this map is obtained by combining together the analysis of floodable areas for each of the five major river districts in Italy.
However, the analysis is performed separately for each district, with methods which can be more or less accurate and which follows different procedures, so it is clear that the results are not always comparable.

Let's for example consider the map related to a medium probability hazard (Figure 1.5), where the extension of floodable areas is shown.
From the map it seems like in Calabria region we have a surprisingly high level of floodable areas if compared with other Southern regions, and it seems like the number of floodable areas is comparable with mountain regions like the Valle d'Aosta. Clearly this cannot be true, and this misleading result is only due to the fact that in Calabria region the evaluation of the levels of flooding was rough, while in Northern regions they applied more sophisticated methods of analysis.

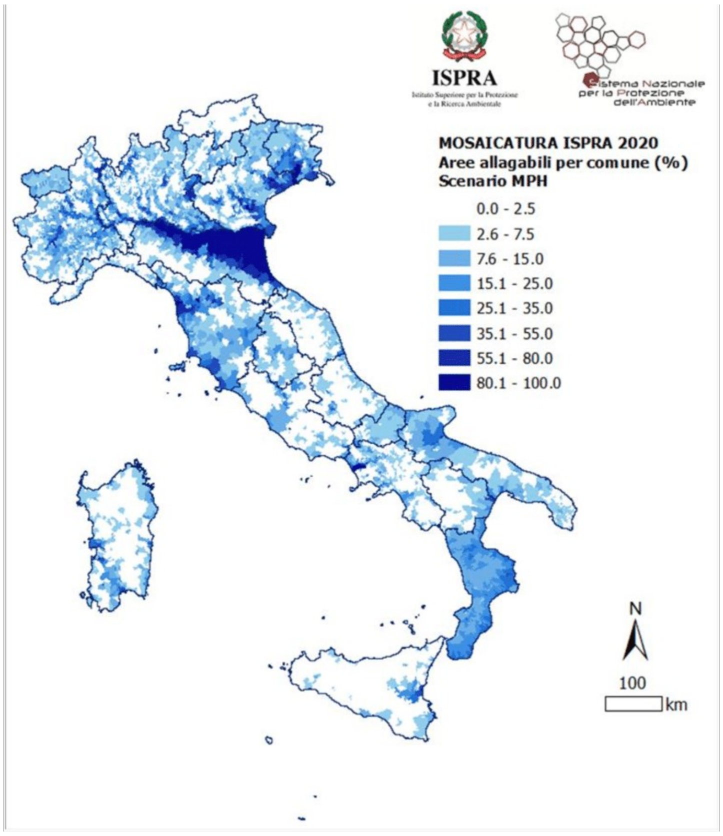

Figure 1.5: Medium Probability Hazard map of Italy

Two things are important to consider when dealing with the issue of flooding: the first is clearly the environmental condition, but equally important and influent on the event of flooding is the land use.
In fact, in one hand we cannot have a flood in absence of waterways or in arid areas. But on the other hand, we can have extremely intense flooding in urbanized areas where natural drainage channels have been reduced or buried or where there is an extensive overbuilding.

In general, what is important to understand is that, in case of extreme rains, water needs to flow down and sometimes drainage channels and/or riverbeds cannot contain the amount of water. This phenomenon cannot be avoided or reduced. What we can do is to design the land use in order to consider additional drainage, define floodplains and avoid extensive urbanization in areas with high level of hazard. In Italy, the phenomenon of unauthorised building, together with an old or absent plan of land use, has been one of the main causes of disasters in the last years, and this is the main reason why we choose this risk as relevant for our analysis.

Finally, there is the issue of energy efficiency. The reason why we chose to consider this factor is that nowadays, it is not possible to make any discussion disregarding the aspect of energy efficiency. This aspect is important not only from the point of view of climate change, but also to reduce the waste of resources, the pollution and also the energy poverty[1] and poor comfort conditions. In fact, both at a European and national level, there are a very large amount of incentives and subsidies aimed at increasing energy efficiency of buildings, installing renewable power plants and so on.

Moreover, Italy is a complex territory also from the point of view of climate. As a matter of fact, in the country we can see the presence of a number of different climate situations (Figure 1.6), ranging from extremely hot (as in Sicily) to extremely cold (Alps regions) hence, a deep knowledge of how to improve buildings efficiency in different climates is crucial, especially in a country like Italy where the majority of fuel and gas is bought from foreign countries (57 million tons of petrol, 73 million cube meters of gas in 2021). [22] [23]

These are the reasons that has driven the choice of seismic and flood and energy efficiency. Of course, many other risks could have been considered, and with our choice the intent is not to say that those are less relevant. However, we had to select a limited number of types of risks and those, from our point of view, are relevant in the perspective of the hazard in Italy, and are also suitable for our analysis.

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[1] Energy poverty is a situation in which households are unable to access essential energy services and products. Energy poverty occurs when energy bills represent a high percentage of consumers' income, or when they must reduce their household's energy consumption to a degree that negatively impacts their health and well-being. [61]

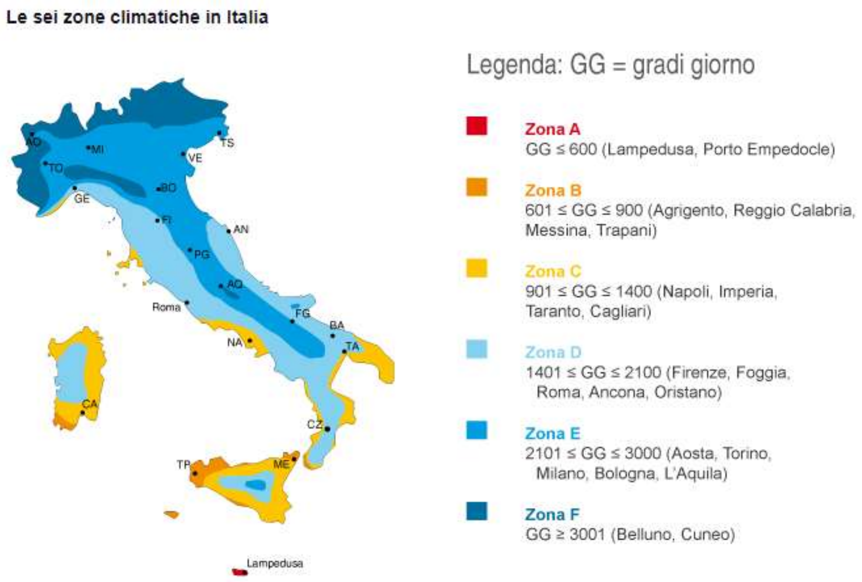


Figure 1.6: the six climate zones in Italy (A hotter, F cooler)

1.2. Description of the method

The aim of the study we are proposing is to evaluate the integrated vulnerability, as previously defined, of a residential building with respect to three risks (seismic, flood and energy efficiency) for the purpose of more effective management of interventions.

For the purpose of this assessment, vulnerabilities to individual risks will first be assessed. Only after obtaining a vulnerability value for each risk can the information obtained be aggregated, depending on the expected economic loss associated to each risk, at the site where the building is located (Chapter 4).

At the first stage of the study, based on the relevant literature, the main factors affecting individual vulnerabilities were identified. These informations were retrieved from different sources, for example, seismic vulnerability factors were obtained partially be the Italian Building Code, where favourable/unfavourable structural characteristics are defined; for energy efficiency, many factors were suggested by the Certificate of Energy Performance. For what concerns flood vulnerability, many factors were retrieved by the Italian damage model INSYDE [26].

Once all factors for all vulnerability classes were identified, we have written a questionnaire describing the methodology and the factors which comes into play. This questionnaire, one for each category of risk, was submitted to experts in each field, asking to give a weight to the individual vulnerability factors identified that is representative of the factor's importance in defining the total vulnerability of the building. In order to have more consistent result, the questionnaires were submitted in the context of a two steps Delphi procedure (Chapter 3). This passage was necessary due to the lack of knowledge and lack of literature regarding the factors involved in the vulnerability of residential buildings and their impact on the final vulnerability, when many of them are considered jointly.

To facilitate the weighting operation, the factors have been expertly grouped into categories. The categories groups together all the factors which belong to a similar field (for example: plant component in buildings). We have asked, first, to associate a weight with each category (Pi), such that the sum of the category weights is unity. Next, we asked to associate a weight (pi) with the factors contained in each category, according to the criterion that within each category the sum of the weights should equal unity.

In this way, the weight of the individual factor will be given by the product of the weight of the category and the weight of the factor within that category. Once the weight of each factor is defined, according to the value it takes, it is possible to compute the vulnerability of a building with respect to one risk. Finally, the vulnerability of the building will be given by the following formula:

$$\sum_{i=1}^{n} P_i \left(\sum_{j=1}^{m} p_j v_j \right)$$

Where:
n = number of categories
m = number of factors within the individual category
P_i is the weight of the category i (i = 1, ..., n)
p_j is the weight of the factor j (j = 1, ..., m)
v_j= value assumed by factor j in category i (appropriately reclassified on a scale from 0 to 1).

At this point of the procedure, we should have obtained the singular vulnerabilities with respect to seismic, flood and energetic risk, which will be labelled V_S, V_F and V_{EE}.

Now we must aggregate this result, based on how much a singular vulnerability is relevant with respect to the total vulnerability of the building. An estimate of this importance can be given by the Expected Annual Loss (EAL), which has been chosen as a measure since:

- Can be evaluated with rigorous procedures and at different scales, depending on the available data;
- Do not introduce other risk elements (like hazard or exposure) hence the results are still a vulnerability.

Therefore, to define expected annual loss at a given location with respect to the three vulnerability we proceeded as follow (Chapter 4):

- for seismic vulnerability we applied the concept of PAM as defined in the Annex A to the DM 65 of 2017 [24];
- for flood vulnerability we applied the main damage models available for Italy as included in the project MOVIDA [25];
- Finally, for energy vulnerability, we considered the cost of the excess of primary energy for a building with a medium level of energy efficiency.

Once we have defined the local monetary losses and defined the relationships between the local losses according to their individual values, we are able to find the integrated vulnerability, so our procedure is complete.

To recapitulate, the steps to obtain the integrated vulnerability are:

1. Definition of the vulnerability factors and the values assumed by them (Chapter 2).
2. Determination of the weights of the vulnerability factors using the Delphi procedure (Chapter 3).
3. Determination of expected annual loss as a weight for vulnerabilities (Chapter 4)
4. Obtaining Integrated Vulnerability Index (in Chapter 5 we will present some application to case studies).

In Figure 1.7 there is a diagram that graphically summarises the entire procedure.

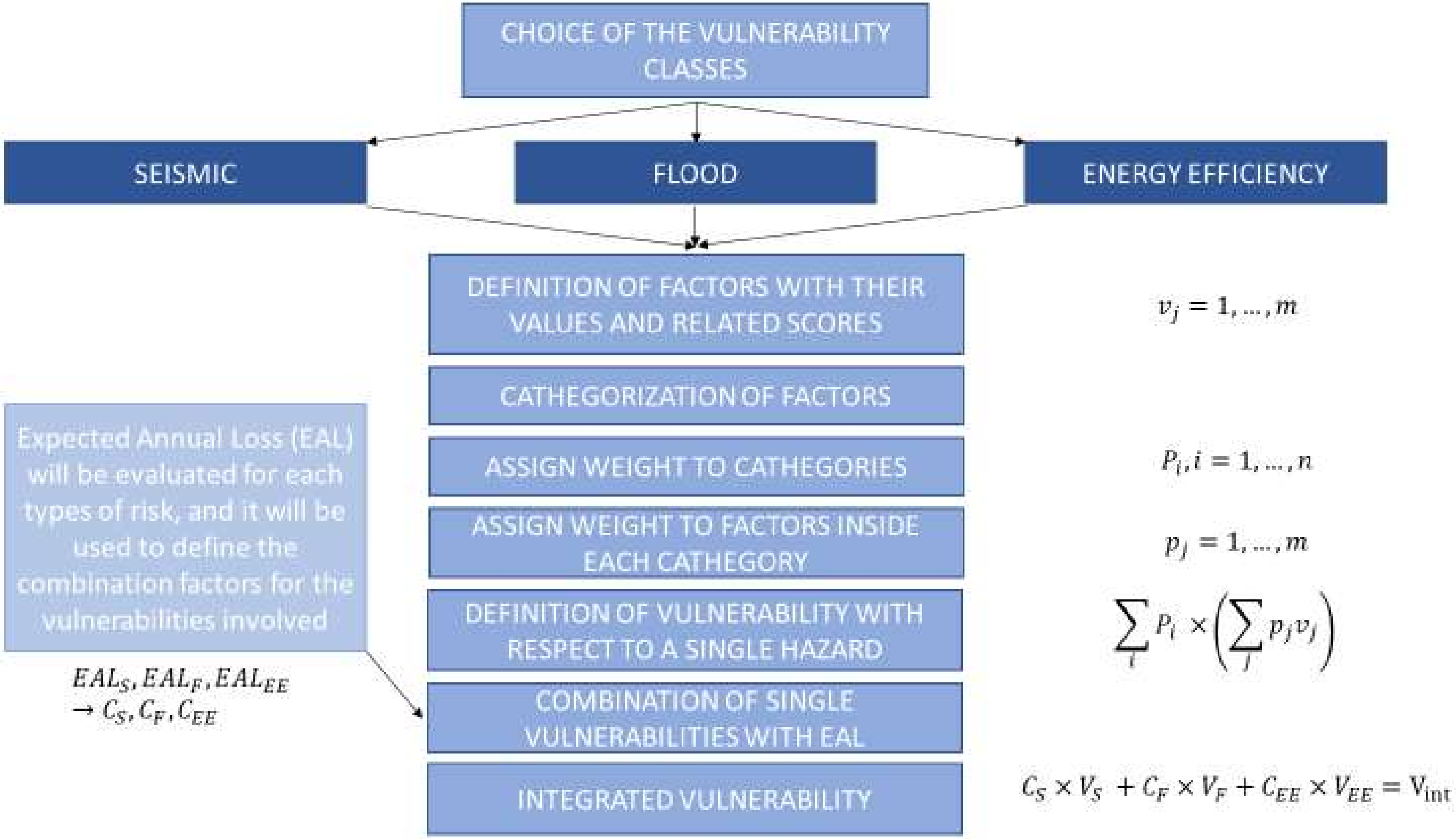


Figure 1.7: Graphical representation of the methodology

2 Definition of factors and values

In Tables 2.5, 2.6, 2.7 we will go on to report, for each factor in each index, what values they assume and their scores, explaining the reasons behind the assigned score. As it can be seen, some values have not been assigned with any weight. This is because at this preliminary stage, we want to hear for expert opinion, which will provide important assessments of both the usefulness of the factors and the values they may take. Also, not all scores of each value correspond to an exact distribution, but an increasing or decreasing trend in vulnerability levels can always be identified. We would also point out that in case the value assumed by a factor should not be present among those listed by us, one can always assign it to one of the already existing classes, or define its score by interpolation between two classes.

Table 2.5: Seismic vulnerability values and scores

Seismic vulnerability factors	Values	Score	Score motivation
Height	1-2 floors 3-4 floors 5-6 floors 7 floors or more	0 0.2 0.6 1	As the height of the building increases, so does the displacements at the top and the inertia forces induced, hence the possibility of a damage increases. In NTC18 Chapter 7 [28], it is clarified that building height limitations should be evaluated according to specific local requirements. In any case, limitations depend on the reference seismic zone. For the choice of values, reference was made to the technical standards of the Abruzzo region, one of the most seismically active in Italy. In the Abruzzo regional standards [32], for ordinary masonry or wood buildings, the limitations impose a maximum of two stories in zone 1 and 7m for wood buildings. This increases to 11m for zone 2 and 16m for zone 3. Considering an average floor height of 3m, we can say that the safest range is for 2-story buildings, followed by 3-4-story buildings, followed by 5-6-story buildings, and finally buildings with a height of more than 7 stories will be the most vulnerable.
Year of construction	Post 2009 1975-2009 Before 1975	0.1 0.7 1	The age of the building influences its vulnerability for two reasons: first, an older structure is more likely to be in poor conditions; secondly and most importantly, structures designed with old regulations are less safe. That is the reason why we

			choose to define the values according to the years in which the building code has been updated, assigning a 0,1 score to structures designed according to the most recent norms.
Foundations	Deep foundations Shallow foundations		We have not assigned scores to this factor since we think that it could be considered not relevant by the experts
Roofing system	Light non-pushing roofs Medium or heavy non-pushing Light pushing Medium or heavy pushing	0 0.33 0.66 1	Roof system transmits horizontal action to walls of the top levels. These actions increase for pushing roof and with the weight of the roof
Slab system	Rigid slab Semi-rigid slab Flexible slab	0 0.5 1	The rigid slab permits the development of a positive box-behaviour. As the slab becomes more flexible, the forces are distributed in un unfair way and we have the developments of differential actions in plan, which can be harmful.
Type of resisting system	RC structures: frame, coupled walls, mixed. Steel structures: framed and with eccentric bracing. Wood structures with nailed light frame panels with nailed diaphragms.	0	Structures capable of resisting and redistributing horizontal actions, with heavenly distributed mass and rigidity, are considered safe against seismic actions.

	RC structures: unbonded or inverted pendulum framed single-story walls. Prefabricated structures: panelled or with embedded columns and hinged horizontals. Steel structures: with eccentric bracing, or framed with concentric bracing. Timber structures with hyper-static portals with cylinder-stemmed means of connection.	0.33	As some of these characteristics are lacking, the seismic performance of the structural system decreases, reaching the worst case for inverse pendulum structures (the majority of the mass is lumped at the higher floors) of ordinary masonry structures, for which we can expect a lack of connection between walls (no box-behaviour). NTC18 in Tab 7.3.II [28] provides guidance on what is the behaviour factor at Life Safety Limit State of different structural systems with respect to seismic actions. The higher the behaviour factor, the greater the reduction in spectral actions and thus the better the seismic performance. On this basis, structural systems were classified.
	Torsionally deformable RC structures. Prefabricated monolithic cell structures. Steel structures with concentric V-shaped bracing. Wood structures with lightweight framed wall panels. Masonry structures: reinforced masonry, reinforced masonry with capacity design, confined masonry with capacity design	0.66	
	Reverse pendulum RC structures. Steel structures: masonry infill, bracketed or reverse pendulum structures. Masonry structures: ordinary or confined	1	
Planimetric configuration	Regularity in plan	0	Regularity (mass / stiffness) in plan permits heaven distribution of forces, avoiding torsional effects, which are one of the main causes of collapse under seismic actions
	Absence of regularity in plan	1	
Configuration in elevation	Regularity in elevation	0	Regularity (mass / stiffness) in elevation permits heaven distribution of forces, avoiding excess shear actions in columns, soft-storey and other collapse mechanism.
	Absence of regularity in elevation	1	

Maximum masonry spacing	Not masonry structures Masonry spacing < 5m Masonry spacing > 5 m			We have not assigned scores to this factor since we think that it could be modified by the experts, and we want to hear their opinion before
Presence of seismic joints	Presence of seismic joints	0		The presence of seismic joints increases the seismic performance of a building, they can also be used to increase regularity in plan
	Absence of seismic joints	1		
		Pre2003	Post2003	Introduction of the new anti-seismic legislation
Seismic intervention	Upgrading Improvement Local interventions No interventions	0 0.33 0.66 1	0 0 0 0	We assume the effects of seismic interventions to be relevant for buildings designed before the introduction of the new seismic norms. For buildings designed after 2003, the design should be good enough not to require interventions.
Architectural components	Floors	0.1		The more massive the architectural components are, and the higher is their position (balconies), the higher is their potential to damage to other parts of the structure or for people. That’s why scores are assigned depending on the dimensions of the non-structural element and on their height [33]
	Furniture and contents, false ceiling	0.4		
	Tiles and other roofing elements, windows and shutters	0.7		
	Projecting elements, such as balconies and parapets, and masonry infill and cladding	1		
Plant components	Installations with accommodation defined at the design stage	0		Plants components can induce vulnerability in the case in which they reduce the capacity of the wall in which they are located. That’s the principle according to which we created the values, and assigned the corresponding scores (if the accommodation has been design, it’s safe, otherwise not)
	facilities added at a later stage, but positioned in a way that does not reduce the load-bearing capacity	0.5		
	facilities added at a later stage of construction, in a position that reduces the load-bearing capacity of the building	1		
State of maintenance	Excellent	0		The state of maintenance is considered to be one of the main elements of vulnerability of a structure. In fact, even if at the design stage everything is made

	Moderate Poor	0.5 1	properly, poor maintenance can increase the possibility of damage, also because we might assume a structure to be more resistant than it actually is.

Table 2.6: Flood vulnerability values and scores

Flood vulnerability factors	Values	Score	Score motivation
Residential type	Detached house Semi-detached house Apartment	0,5 0,75 1	Depending on the residential typology, the type of organisation of the common areas varies and the distribution of the installations varies, together with the number of floors, materials employed and so on. Therefore, together with the residential type, vulnerability also varies
Year of construction	Post 2009 1975-2009 Before 1975	0.2 0.7 1	The age of the building influences its vulnerability for two reasons: first, an older structure is more likely to be in poor conditions; secondly and most importantly, structures designed with old regulations are less safe.
Construction material	Reinforced Concrete Mixed Stone/masonry Timber	0,1 0,2 0,4 1	The vulnerability associated to different construction materials increases with the propensity of the material itself to be damaged by the action of water. For this reason, we assume that RC, mixed and stone/masonry materials have low scores, while timber is highly vulnerable, since prolonged contact with water can cause the timber to mildew, even irreversibly
Exterior walls cladding	Stoneware Bricks or exposed stones Non-isolated plaster Isolated plaster	0,1 0,25 0,8 1	The score associated to the exterior claddings depends on the expected damage that they suffer at contact with water. Isolated plaster is a porous material that, if plunged in water, loses its functionality and must be completely substituted. The opposite behaviour is found for stoneware, that is expected to suffer null or minor damage at contact with water.
Interior walls material	RC/ glass block Bricks Plasterboard /timber	0.2 0.4 1	See construction material

Interior wall cladding	Ceramic/washable plaster	0		See Exterior wall cladding
	Plaster	0.75		
	Paper/wood	1		
Floor material	resin/cement/ceramic	0.2		The score associated to the floor material depends on the expected damage that it suffers at contact with water. Wooden floors and tapestry, if plunged in water must be completely substituted. The opposite happens for resin, cement o ceramic floors, that are expected to suffer null or minor damage at contact with water.
	stone/PVC	0.6		
	parquet/moquette	1		
Number of floors	More than 1	0,5		In the case of a single floor, the only option is to place every plant, valuable good, etc at the first level, and in this case, we can suffer high damage in the event of a flood. Differently, if we have more than one floor, we have the possibility to relocate damageable elements to save them from the action of water.
	1	1		
Presence of basement floor	Yes	0		The presence of basement is always an element of vulnerability for buildings in floodable areas, since the water flows toward the basement that can be flooded also with moderate water heights.
	No	1		
Ground floor elevation	hg > h(P1)	0		The ground floor elevation is referred to the expected flood height for different floodable zones. If the ground floor is located below the floodable elevation in hazard zone P3 (highest probability of occurrence) it will be in the highest vulnerability case. On the other hand, the case of lowest vulnerability is when the ground floor is above the elevation of hazard zone P1 (lowest probability of occurrence). For buildings for which data relative to the expected water height aren't available, we refer to an historical event and we assume only the case in which the ground floor elevation is higher (0,2) or not (1).
	h(P2) < hg < h(P1)	0,33	0,2	
	h(P3) < hg < h(P2)	0,66	1	
	hg < h(P3)	1		
Floodable floor opening	Absence of manholes and openings area < 30% total outdoor surface area	0		In the case of floodable floors, it is important to evaluate the openings that could make it easier for water to flood into them. For sure, the presence of manholes is one main way through which water can enter floodable floors (higher scores). Secondly,
	Absence of manholes and openings area > 30% total exterior surface area	0,4		
	Presence of manholes and openings area			

	< 30% total exterior surface area Presence of manholes and openings area > 30% total outdoor surface area	0,7 1		we can also consider the number of openings as an element that increases the vulnerability
Presence of check valves	Yes No	0 1		Check valves are elements applied to the plumbing systems which avoid the water to flow back from the plumbing system to the inside of the building when the pressure in pipes grows, as it happens during floods. Hence, their presence is an element of safety with respect to floods.
Floodproofing measures	Wetproofing and dryproofing measures Wetproofing measures Dryproofing measures No	0 0,4 0,6 1		Floodproofing measures, when designed correctly, can offer significant protection to the structure. A good combination of wetproofing and dryproofing measures can almost eliminate the risk due to flood, while the presence of one of the two measures singularly can anyway offer some protection.
Electrical system position	hg > h(P1) h(P2) < hg < h(P1) h(P3) < hg < h(P2) hg < h(P3)	0 0,33 0,66 1	0,2 1	The location of plants is referred to the expected flood height for different floodable zones. Therefore, if the plant is located below the floodable elevation in hazard zone P3 (the one with the highest probability of occurrence and so lower water height) it will be in the highest vulnerability case. On the other hand, the case of lowest vulnerability is when the plant is above the elevation of hazard zone P1 (zone with the lowest probability of occurrence and so higher water height).
Plumbing system position	hg > h(P1) h(P2) < hg < h(P1) h(P3) < hg < h(P2) hg < h(P3)	0 0,33 0,66 1	0,2 1	See electrical system position
Thermal system position	hg > h(P1) h(P2) < hg < h(P1) h(P3) < hg < h(P2) hg < h(P3)	0 0,33 0,66 1	0,2 1	See electrical system position

Heating system type	District heating Independent heating Centralized	0 0,75 1		Centralized heating system has the higher score in vulnerability since the cost of the plant is higher with respect to independent heating. District heating has the heat generator located outside the building, hence has the lowest score.
AC system position	hg > h(P1) h(P2) < hg < h(P1) h(P3) < hg < h(P2) hg < h(P3)	0 0,33 0,66 1	0,2 1	See electrical system position
Emission terminals	Radiators Radiant floor panels/thermal convectors	0.1 1		The vulnerability of emission terminals depends on the possibility of the terminals to be functional after the contact with water. Radiators can still be functional, suffering maybe only aesthetic damage. Radiant floors panels and thermal convectors on the other side may completely be lost after a flood, and so they are assigned with the highest vulnerability score.

Table 2.7: Energy efficiency values and scores

Energy efficiency factors	Values	Score		
Height/n-er of floors	1-4 floors	0.5		The compactness of a structure ensures higher energy efficiency, so a lower number of floors is generally recommended. Moreover, for squat buildings, there's a higher roofing surface with respect to the floor surface as well as minor costs for elevators and pumping of fluids toward higher floors
	> 4 floors	1		
Surface-to-volume ratio	S/V < 0,4	0		The compactness is the reason behind the scores assigned to the Surface to Volume ratio. The greater the surface area, the greater the potential heat gain or loss through it. Consequently, a small S/V ratio implies minimum heat gain and heat loss. [34]
	0,4 < S/V < 0,7	0.5		
	S/V > 0,7	1		
Windows-to-walls ratio	<15%	1		The WWR has an important impact on the efficiency of a building. In Italian climate conditions, the typical trend of global primary energy demand of buildings versus WWR is shown in Figure 2.1. [35]
	15-30%	0.5		
	30-50%	0		
	>50%	1		
Year of construction	post 2015	0,2		The year of construction of the building influences its vulnerability for two reasons: first, an older structure is more likely to be in poor conditions; secondly and most importantly, structures designed with old regulations are more likely to be, on average, less efficient.
	2005-2015	0,4		
	1991-2005	0,6		
	1973-1991	0,8		
	pre 1973	1		
		ABCD	EF	The following factors have values' scores dependent on the climatic class
External wall stratification	Massive insulated structure	0,2	0,2	the layering of walls has a different impact depending on the climate. Therefore, in the case of colder climates (E, F) the more massive and insulated the structure, the better the energy performance. On the other hand, this is not the case for warmer
	Light insulated structure	0,75	0,45	
	Massive non-insulated structure	0,45	0,75	
	Lightweight non-insulated structure	1	1	

				climates, where the better energy performance comes from the massiveness rather than the insulation of the layering
Stratification of slabs towards the outside or unheated rooms	Massive insulated structure Light insulated structure Massive non-insulated structure Lightweight non-insulated structure	0,2 0,75 0,45 1	0,2 0,45 0,75 1	See External walls stratification
External wall cladding	Clear cladding Dark cladding	0.2 1	1 0.2	Dark colour of the façade traps more thermal energy than clear colours. Hence, clear colours are better in hot climate (classes ABCD) while dark colours are better in the case of cold climate (classes EF)
Type of window frame	Thermal break frame and triple glazing Thermal break frame and double glazing Frame without thermal break and single glass	0 0.5 1		Windows have a major impact in the exchange of energy between the building and the environment. The more the type of window frame is able to reduce the exchange of heat (thermal break frame and triple glazing) the more we increase energy efficiency, and vice versa. This is true both for winter and summer (or cold and hot climate).
Solar shading	Movable solar shading Fixed solar shading Absence of external solar shading on glazed surfaces	0 0.5 1		The possibility of having a solar shading is very important is the evaluation of the energy efficiency of a building. The case in which we have movable solar shading is the best case since we can choose to employ it or not, according to the weather, and it's associated to a null score. The middle score is associated the fixed shading, where we don't have the possibility, for example in winter, to remove the shading. However, it is worse the case of absence of shading, to which we associate score 1.
Energy Performance Certificate	A4 A3-A2 A1-B C-D	0 0.1-0.2 0.3-0.4 0.5-0.6		The energy performance certificate assigns a class to a building, or an apartment, depending on its level of energy efficiency. Higher the class of the EPC, the more the building is efficient. For this reason, we assign increasing scores to increasing values of the EPC.

	E-F G o Assente	0.7-0.8 0.9-1	
Type of emission terminals	Radiant surfaces Fancoils or air terminals Radiators	0.2 0.6 1	The scores assigned to different typologies of emission terminal depend on how efficient they are in transferring the heat from the plant to the environment. Radiators are the less efficient terminals, while radiant surfaces (such as floor radiant panels) are the most efficient.
Type of system regulation	Climate regulations Thermostat / on-off	0 1	The type of system regulation can be either thermostat or more advanced systems such as climate regulation. The latter are considered more efficient since they permit to maintain the inside temperature constant, which is proven to consume less energy with respect to the on-off system of regulation
Type of DHW production system	Solar thermal system/heat pump Boiler powered by fossil fuels Electric boiler	0 0.7 1	The score assigned to the different typologies of plants for the production of domestic hot water depends on the efficiency of the plant. Heat pumps and plans powered by solar system are the most efficient, on the contrary, electric boiler is considered the least efficient.
Presence of systems powered by renewable resources	> 2 kW 1-2 kW <1 kW No	0 0,4 0,7 1	The presence of renewable resources is a factor that increases the total efficiency of the building. Hence the sores assigned to this factor depends of the presence of renewable resources, and if this is the case, on how much energy is produced by renewable resources.
Type of heating system	Centralized with thermoregulation/ energy metering Autonomous Centralized without thermoregulation/containment	0,2 0.7 1	The score assigned to the different typologies of heating system depends on the efficiency of the plant. Centralized systems with thermoregulation are the most efficient, on the contrary Centralized systems without thermoregulation are considered the least efficient.
A/C system	Absent	0 |0,2	The presence of the A/C system is in any case an additional source of energy consumption. Hence, the best score (null) is

	Centralized system Autonomous (split or similar)	0,4 1	assigned where the plant is absent (EF), while the worst scores are assigned to the presence of A/C systems, depending on their energy consumption. In climate zones (ABCD) to the absence of A/C is given a score of 0,2 in order to consider the lack of comfort.
Type of heat generating system	Heat pump / biomass system Hybrid system (boiler + heat pump) / district heating system Condensing boiler fired by fossil fuels Traditional boiler fired by fossil fuels	0,2 0,4 0,8 1	The score assigned to the different typologies of heat generating system depends on the efficiency of the plant. Heat pumps and biomass systems are the most efficient, on the contrary traditional boiler fired by fossil fuels are considered the least efficient. The other possible typologies are considered in the middle. None are assigned with a null value.
Presence of controlled mechanical ventilation system	yes, with heat recovery yes, without heat recovery no	0 0.5 1	The presence or a mechanical ventilation system is considered a good way to maintain the comfort conditions inside a structure while saving energy. Therefore, the presence of such a system is considered as the best case with null score, when in presence of heat recovery. The absence of these plants is the worst case, with unit score.

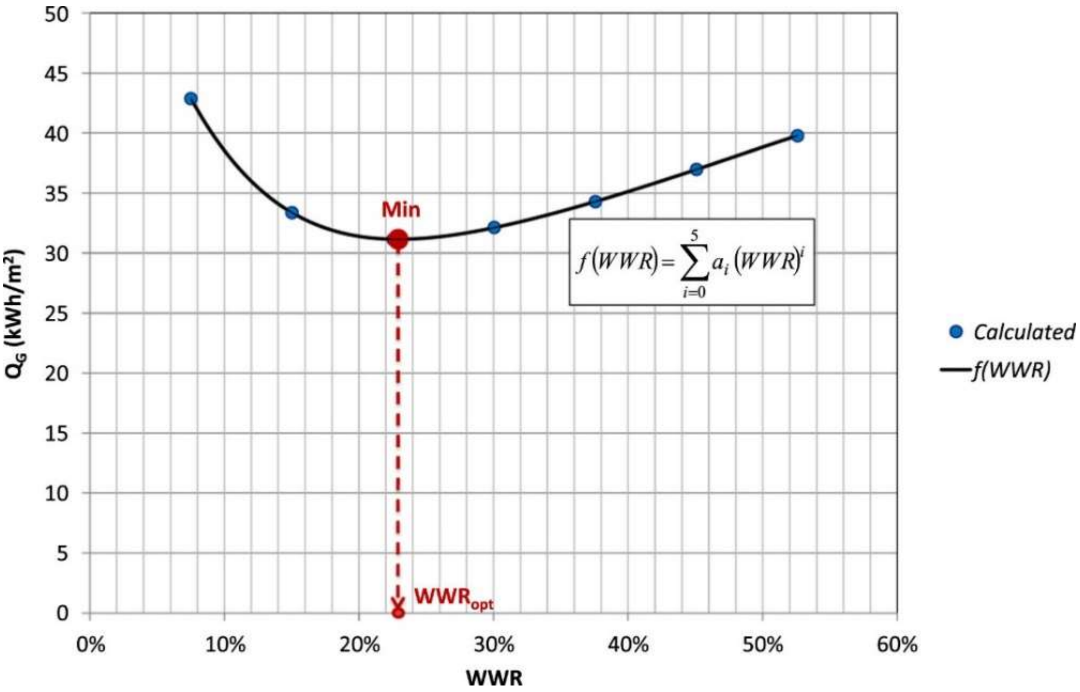


Figure 2.1: Energy consumption with respect to WWR

3 Application of Delphi methodology

3.1. Description of Delphi method

The Delphi method is a research tool used to facilitate and structure a group communication process aimed at enabling its constituent individuals to generate ideas, address and find solutions to complex problems [36] through an iterative investigation aimed at transforming individual opinions into group consensus. [37]

One of the reasons behind this procedure is the limitations associated with the comparison of opinions by means of unstructured communication, which is considered insufficient to bring out a point of agreement even with small groups (in this specific case, our groups consisted of only a few participants), due to the lack of systematicity in the procedures and the psychological effects implied by mutual prejudices.
This method allows everyone to understand the assumptions and opinions underlying the judgements on a topic made by each expert. At the end of each round, the results are analysed, thus offering participants the opportunity to follow the progress of the research by reading each other's opinions in full respect of anonymity. [38]

When to use it? In principle, its use is preferable when:

- the problem cannot be analysed with precise analytical techniques but can be better developed through subjective judgements;
- face-to-face is not possible;
- there is not the availability of resources and time to organise the necessary meetings and disagreement between subjects might suggest that subjects feel freer when protected by anonymity;
- the heterogeneity of the panel should be safeguarded, avoiding the phenomena of leadership and/or passive adaptation. [39]

In our case, we applied the Delphi methodology to evaluate the weight associated to each factor of the vulnerability indices. This method is particularly appropriate, as:

- there are no precise analytical techniques for determining the factor’s weights of the vulnerability indices we are constructing, so there is a need for the subjective judgement of experts;
- we did not have the resources or time to organise face-to-face meetings with experts;

- we wanted to involve both Italian and international experts in order to have a heterogeneous panel.

All of this considered, we believe that the application of a Delphi methodology is suitable and adequate for the type of research we are carrying out.

We will therefore opt for a two-steps Delphi methodology: at a first stage we will collect general concordances, in the second stage we will improve the concordance of the results.

The Delphi technique is a typical methodology of social research, which makes it possible to interview a selected group (also known as a panel) of experts, (which for us will be made up of risk or energy efficiency experts), called upon to express, anonymously, their opinions and views on a given issue, in order to validate certain traits through mutual comparison and progressive sharing, thus creating a creative and structured communication process.

This technique envisages successive phases of data collection, characterised by the use of social research tools of various kinds (we chose to use questionnaires) and aimed at a progressive exploration and evaluation of the topic in question. To this end, the interviewer has the task of mediating the comparison and evaluating the opinions collected, favouring the synthesis of the judgements collected in each phase with the results of the previous one. [40]

The first experiments with the standard Delphi technique date back to the 1960s. Despite continuous changes, the method has always been based on four main characteristics [...]: Anonymity, iteration, controlled feedback and group response statistics [41]. In order for a Delphi to be well structured, it is important that these features are not missing. Specifically:

- Anonymity: each expert receives the questionnaire from the moderator and answers the questions. All this takes place in total anonymity, only the moderator is aware of the identity of the experts. This feature is crucial because it allows us to override certain inefficiencies typical of face-to-face meetings such as the presence of a dominant individual who might, even unintentionally, influence the judgement of others [42] or lose the focus of the study because he or she is busy trying to be right about those who do not think the same way. Furthermore, by guaranteeing anonymity, some individuals may feel more comfortable expressing uncomfortable ideas and opinions that could generate debate. Based on this, it is not a leap to say that anonymity plays a crucial role and that concealing the identity of participants may even lead to a higher response rate. [43]
- Iteration: the Delphi method consists of a survey done in several rounds. Dividing the research into rounds allows experts to review their answers and compare them

with the aggregated results of the previous round, and allows moderators to modify the questionnaire if they deem it necessary.

- Controlled feedback: once the round is over, the moderator analyses the individual responses and prepares an aggregate feedback that will be sent to the experts. This allows the experts to 'communicate' with each other, in effect, without knowing the identity or response of the individual. Iteration and feedback together allow convergence towards group consensus.
- Group response statistics: this is used to understand whether consensus has been reached or not. Mathematical and statistical tools are used for this purpose. [62]

The standard Delphi procedure has not undergone any substantial innovations over the years, and consists of the following steps (Figure 3.1):

1) Preliminary investigation: To be effective, the Delphi questionnaire is always preceded by a preliminary investigation. The exploratory phase is of crucial importance. If respondents do not understand the purpose behind the application of the Delphi technique, they may respond inappropriately, become frustrated, or lose interest [44]. It is worthwhile, therefore, to initiate a preliminary phase to reassure the experts that they will be able to complete the required task. To this end, individual contact and providing appropriate information material in advance is often very effective. [45]. This phase consists of:
    a. A desk research (preliminary research on the documentation relating to the subject under investigation) that allows the objectives to be focused and the people to whom the questionnaire will be administered to be defined.
    b. Constitution of the working team. The criterion for constructing a Delphi expert panel is not (and cannot be) merely statistical. The size of the expert panel is variable. The literature claims that good results can always be achieved with a homogenous group of experts with small panels of 10-15 people. The sample size must be increased considerably in the event that several reference groups are involved. [44]

    In our case, the preliminary research was carried out by the undersigned together with professors who are experts in the fields of seismic risk, flood risk and energy efficiency. The desk research consisted in the identification of the factors which composes the indices to be submitted to the panels; the working team consisted on three panels, one for each risk analysed, composed of Italian and international experts. The fundamental criterion used in the selection of the members of the three panels was expertise, i.e. 'knowledge' and practical experience on the topics investigated. [38] Each one of the three panels were provided with the vulnerability questionnaire associated with the corresponding risk class (Appendix A), composed of categories, factors and values identified during the desk research. The preliminary phase lasted approximately one month.

2) Iterative phase: in phase 1, a questionnaire is proposed to the panel concerning the problem to be assessed. The determination of the subsequent questionnaires, stage 2 or later, which will be repeated, is based on the answers from the previous stages. In this way, it is the panel itself that defines the elements of the problem to be investigated, based on the experience and knowledge of the individual members.
   In most cases, the first questionnaire poses the problem broadly and asks for answers and comments. The answers are summarised by the research team and used to construct a second questionnaire. The second questionnaire presents the results of the first one and gives the respondents the opportunity to review their initial answers in the light of the feedback that includes the answers of the entire group. During this interactive process, which can be repeated whenever deemed appropriate, problems are highlighted and areas of agreement or disagreement identified. [46]

In our research, an initial questionnaire was submitted to the panel of experts containing, for each risk class, the vulnerability factors that were identified as relevant during the desk research; each of the participants was invited to express evaluations concerning the weight of each factor, comments concerning the contribution of these factors and also suggestions on possible additions and/or modifications to the factors and vulnerability categories (Appendix A).

All feedback, both numerical and verbal, are then collected, summarised and shared anonymously with the other panel's members who, in the second phase, will be able to revise their opinion, until a consensus of opinion is reached.

In the case of the flood vulnerability index, the results of phase 1 had a good level of concordance between the members of the panel of flood experts, so the phase 2 questionnaires were constructed ad hoc for each panel member, so that each one could focus attention only on the opinions they expressed that most disagreed with the general trend. (Appendix B, example of one questionnaire)

For the seismic vulnerability questionnaires, we still had good concordance of opinions among the members of the panel. However, the majority of experts suggested to revise the structure of the vulnerability index as a whole. Therefore, the seismic vulnerability index was restructured according to the experts' suggestions and the following phase 2 questionnaire was provided to all experts in the same format, without adopting a customized questionnaire for each member of the panel (Appendix B)

Finally, for what concerns the energy efficiency questionnaires, we had a very low level of feedback from the panel, hence, due to the time constrains, it was not possible to proceed to a phase 2. We will assume as finals the weights obtained from phase 1. Nevertheless, we suggest a more accurate evaluation of these factor's weights.

3) Data processing: A crucial element is the choice of data processing method. For quantitative data analysis and consensus research, the interquartile range (IQR) is generally used, which is considered a valid tool for measuring consensus in most cases in the literature. The interquartile range measures the dispersion from the median, i.e. the difference between the third and first quartile [47].

   In our case, however, the small number of panel members suggests that statistical methods are not the most appropriate for analysing the results. In step 1, for each factor, we took the mode of the values expressed by the panel and the maximum deviation from the mode. Where the maximum deviation is positive we increased the value of the mode, where the maximum deviation is negative vice versa, in order to obtain a value that was satisfactory for the greatest number of opinions expressed. For the factors for which a modal value was not present or was not unique, we suggested a value such that was satisfactory for the largest number of opinions. The subjectivity of this procedure is evident, which we nevertheless attempted to perform while remaining close to objective criteria.

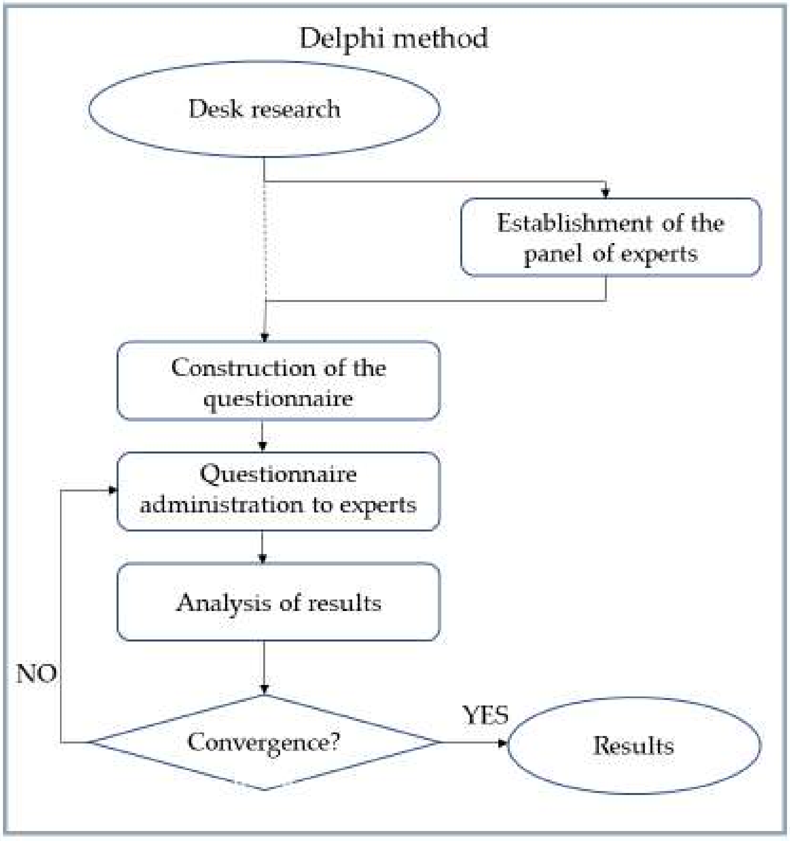


Figure 3.1: Visual representation of Delphi method

It is worth emphasising that the procedure required an analysis of the results that was in part subjective, also in view of the fact that the sum of the weights of the factors in a category must be 1, so the use of the mean, or mode, does not always satisfy this criterion and a rearrangement of the values is therefore required.

The same type of criterion was used to obtain the final results, extrapolated from the answers of the phase 2 questionnaires.

3.2. Phase 1

The phase 1 questionnaires are the result of desk research (Chapter 2). During the desk research we defined, for the seismic and flooding vulnerability indices and for the energy efficiency index, which factors contribute to the determination of vulnerability and the purpose of the Delphi procedure is to determine what weight each factor gives to the total vulnerability (see Chapter 2 for details of the factor weighting method). Since this is the first interview phase, in phase 1 we are interested not only in the weights that the experts will attribute to the factors, but above all in their opinion regarding the structure of the proposed vulnerability indices, the need for modifications in the factors, etc. Below we will see what the responses to the first stage were and what conclusions we drew.

3.2.1. Results of questionnaires on seismic risk

In analysing the results of the questionnaires, one observation above all was crucial. This concerns the fact that the impact of structural characteristics on the seismic vulnerability of a building cannot disregard the identification of the building material.

In fact, the experts emphasised that reinforced concrete or masonry buildings have different elements of vulnerability and that certain factors, for different construction materials, have a different weight.
Therefore, having welcomed this statement, it was decided to modify the vulnerability indices in such a way as to classify buildings into two classes, reinforced concrete and masonry, since they represent the majority of residential buildings in Italy.

In particular, the majority of experts maintain that the factors in category 1 and category 2 should have different weights depending on whether the building is made of reinforced concrete or masonry. Instead, the factors in category 3 can be weighted equally for the two building materials.

Below are the answers given by the experts (weight proposed by experts) and next to them the analysis of the data and the values proposed by us (proposed value) for some factors.

We would like to point out that in the comments, most of the experts specified that the weight assigned refers to masonry buildings. Therefore, we deduced from the first phase how to modify the indices and deduced some values to be proposed in the phase 2 questionnaires for masonry buildings and reinforced concrete buildings.
In Table 3.1 this distinction is not yet explicit, but will be in the phase 2 questionnaires.

Table 3.1: results for seismic vulnerability questionnaires in phase 1

	Weight proposed by the experts						Modal value	Deviation	Proposed value
Category 1	0.5	0.4	0.4	0.6	0.625	0.4	0.4	0.225	0.45
Height	0.2	0.2	0.15	0.15	0.2	0.125	0.2	-0.75	0.15
Year	0.1	0.2	0.25	0.25	0.4	0.3	0.25	0.15	0.25
Resisting system	0.4	0.2	0.25	0.15	0.16	0.075	[-]		
Foundation	0.05	0.1	0.05	0.1	0	0.3	0.05/0.1		0.05
Roofing system	0.05	0.1	0.2	0.2	0.08	0.05	0.05	0.15	0.15
Slab system	0.2	0.2	0.2	0.25	0.16	0.1	0.2	-0.1	[-]
	Weight proposed by the experts						**Modal value**	**Deviation**	**Proposed value**
Category 2	0.5	0.2	0.2	0.2	0.25	0.3	0.2	0.3	0.25
Plan configuration	0.5	0.4	0.2	0.45	0.4	0.5	0.4	0.1	0.4
Configuration in elevation	0.5	0.4	0.5	0.35	0.6	0.5	0.5	-0.15	0.5
Spacing between masonry	0	0.2	0.2	0.2	0	0	0.2	-0.2	0.1
	Weight proposed by the experts						**Modal value**	**Deviation**	**Proposed value**
Category 3	0	0.4	0.4	0.2	0.125	0.3	0.4	-0.275	0.3
Seismic joints	0.3	0.15	0.25	0.15	0	0.1	0.15	+0.15	0,19
Interventions	0.3	0.3	0.25	0.3	0	0.4	0.3	-0.3	0.3
Architectural components	0.3	0.25	0.125	0.1	0.2	0.1	[-]	[-]	0.15
Plants	0.1	0.1	0.125	0.1	0	0.1	0.1	-0.1	0.1
State of maintenence	0	0.2	0.25	0.35	0.8	0.3	Here, the values 0 and 0.8 are clearly extremes and should not be consider for the estimate. The majority of values are between 0.2 and 0.35, hence we chose 0.26		

We want to stress that, even if the reasoning of proposing values was made on a rigorous basis, there was always a critical reasoning behind each weight assigned.

For example, for the factor "roofing system" we chose as modal value 0.05 instead of 0.2 because it also satisfied the opinion 0.08. Similar considerations were made for other factors, not only on analytical basis but also with a subjective approach, focused on reaching the most satisfactory result for all experts.

This is also the reason why we were not able to provide a suggestion for the weight for all the factors.

3.2.2. Results of questionnaires on flood risk

For the flood risk questionnaires, we received no comments or suggestions on formal changes to the flood vulnerability index factors.

The experts made their judgement regarding the weight of the factors and justified their response. Therefore, below are the responses and values we proposed for the second stage.

Table 3.2: results for flood vulnerability questionnaires in phase 1

	Weight proposed by the experts						Modal value	Deviation	Proposed value
Category 1	0.275	0.15	0.5	0.5	0.25	0.25	0.25	0.25	0.3
year	0.025	0.1	0.1	0	0.1	0.05	0.1	-0.1	0.07
residential typology	0.125	hazard dependent	0.15	0.2	0.1	0.05	There is no modal value, but a low weight satisfies the majority of opinions, hence we chose 0.1		
construction materia	0.075	hazard dependent	0.35	0.3	0.1	0.1	0.1	0.25	0.14
external walls cladding	0,175	hazard dependent	0.1	0.3	0.2	0.1	0.1	0.2	0.14
interior walls material	0.05	hazard dependent	0.15	0.1	0.1	0.2	0.1	0.1	0.12
internal walls cladding	0.325	hazard dependent	0.1	0.05	0.2	0.25	Since there is no modal value, we took a value in between 0.2 and 0.25, that being relatively high can also satisfy 0.325. Hence, we choose 0.21		
floor material	0.225	hazard dependent	0.05	0.05	0.2	0.25	In this case the modal value is 0,05, but a value between 0.2 and 0.25 satisfies a larger number of answers, hence we chose 0.22		
	Weight proposed by the experts						Modal value	Deviation	Proposed value
Cathegory 2	0.6	0.6	0.35	0.3	0.5	0.4	0.6	-0.3	0.45
Number of floors	0.025	Low	0.1	0.05	0.05	0.05	0.05	0.05	0.05
Presence of basement floor	0.325	High	0.25	0.05	0.25	0.025	0.25	0.075	0.25
Hg	0.27	Very high	0.25	0.2	0.25	0.15	0.25	-0.1	0.25
Floodable floors opening	0.14	[-]	0.15	0.3	0.15	0.1	0.15	0.15	0.14

Presence of check valves	0.12	High for moderate floods	0.1	0.1	0.15	0.15	in this case there is an equal frequency of the values 0.1 and 0.15, the intermediate value of 0.12 satisfies all opinions		
Floodproofing measures	0.12	high when measures are effective	0.15	0.6	0.15	0.3	0.15	0.45	0.19
	Weight proposed by the experts						**Modal value**	**Deviation**	**Proposed value**
Category 3	0.125	0.25	0.15	0.2	0.25	0.35	0.25	-0.125	0.25
electric plant position	0.25	High	0.2	0.15	0.25	0.2	0.25	-0,1	0.2
plumbing plant position	0.15	High	0.05	0.15	0.15	0.25	0.15	±0.15	0.15
thermal plant position	0.215	High	0.2	0.15	0.2	0.25	0.2	±0.05	0.2
thermal plant typology	0.02	Low	0.35	0.3	0.1	0.15	In this case, the value 0.02 is clearly outside the ranges expressed by other experts. Therefore, a value of 0.2, intermediate between 0.1 and 0.35, was chosen.		
A/C plant position	0.125	High	0.05	0.15	0.2	0.1	there is no mode, but between the values of 0.1 and 0.2 most values are to be found. Therefore, the value 0.15 was chosen		
emission terminals	0.15	Low	0.15	0.1	0.1	0.05	0.15	-0.1	0.1

3.2.3. Results of questionnaires on energy efficiency

For the flood risk questionnaires, we received no comments or suggestions on formal changes to the flood vulnerability index factors.

The experts made their judgement regarding the weight of the factors and justified their response. Therefore, below are the responses and values of weights obtained from the analysis of data.

We are not going to undergo a second phase of the Delphi methodology for the energy efficiency, since there has been a poor feedback from the panel. For this reason, the results labelled as "weights" in the table are going to be the final weight to insert in the questionnaires. We are aware that the results are still rough, hence we suggest a further analysis in the case of application of the methodology, in order to define more accurate values for the energy efficiency factors.

Table 3.3: results for energy efficiency questionnaires in phase 1

	Weight proposed by the experts					**Modal value**	**Deviation**	**Weights**
Category 1	0.2	0.2	0.1	0.15	0.3	0.2	-0.1	0.165
Surface/Volume ratio	0.5	0.4	0.2	0.3	0.4	0.3	±0.1	0.35
N of floors	0.15	0.1	0.5	0.1	0.2	0,1	+0.4	0.25
Windows to wall ratio	0.35	0.5	0.3	0.6	0.4	0.6	-0.3	0.4
	Weight proposed by the experts					**Modal value**	**Deviation**	**Weights**
Category 2	0.45	0.5	0.2	0.35	0.3	0.35	+0.15	0.375
Year of construction	0.3	0.2	0.2	0.25	0.2	0.2	+0.1	0.25
External walls stratification	0.2	0.2	0.15	0.0625	0.15	0.2	-0.1375	0.18
Stratification of slabs towards the outside or unheated rooms	0.2	0.05	0.25	0.0625	0.15	0.0625	+0.1875	0.1
External walls cladding	0.02	0.1	0.05	0	0.1	0	0.1	0.05

Type of window frame	0.18	0.15	0.15	0.25	0.15	0.15	+0.1	0.18
Solar shading	0.1	0.1	0.25	0.125	0.1	0.1	+0.15	0.15
E.P.C.	0	0.2	0.05	0.25	0.15	[-]	[-]	0.09
	Weight proposed by the experts					**Modal value**	**Deviation**	**Weights**
Category 3	0.35	0.3	0.7	0.5	0.4	0.5	±0.2	0.46
Type of emission terminals	0.05	0.05	0.05	0.15625	0.1	0.05	+0.105625	0.1
Type of system regulation	0.05	0.1	0.05	0.15625	0.1	0.05	+0.105625	0.1
Type of DHW production system	0.15	0.05	0.1	0.25	0.15	0.15	±0.1	0.15
Presence of installations powered by renewable sources	0.25	0.2	0.4	0.03125	0.15	[-]	[-]	0.2
Type of heating system	0.05	0.2	0.05	0.03125	0.1	0.05	+0.15	0.05
Summer air-conditioning system	0.15	0.15	0.15	0.0625	0.1	0.15	-0.0875	0.14
Type of heat generator	0.25	0.2	0.15	0.1875	0.15	[-]	[-]	0.2
Presence of controlled mechanical ventilation system	0.05	0.05	0.1	0.0625	0.15	0.05	+0.05	0.06

3.3. Phase 2

The analysis of the phase 1 questionnaires made it possible to draw up the phase 2 questionnaires (Appendix B). Phase 1 was mainly useful to understand:

- whether the structure of the vulnerability indices was shared by the panel of experts;
- whether factors considered in the vulnerability indices were considered significant by the panel and whether there were other significant factors that had been overlooked by us;
- what were, in general, the weights of the factors that were agreed upon by the majority of the experts.

Having generally framed the areas of agreement, phase 2 allows us to refine the study and achieve greater agreement between the experts' opinions.

3.3.1. Results questionnaires on seismic risk

The phase 2 questionnaires concerning the seismic vulnerability index are modified, compared to phase 1, to include a division of the factors in categories 1 and 2 between masonry and reinforced concrete buildings.

Furthermore, in category 2, for reinforced concrete buildings the factor 'maximum distance between masonry' is replaced by 'distribution of infills' according to suggestions supplied by experts. This factor will be assigned with two scores: regular (0) and non-regular (1) where non-regular stands for a distribution of infills capable of causing collapse mechanism such as short columns.

Table 3.4 shows the updated seismic vulnerability index, the proposed value for some factors, the weights assigned by the experts and finally the final result of the analysis, which will be used as the final weight of the seismic vulnerability factors.

As we had imagined, the factor “foundation” will be eliminated for both reinforced concrete and masonry structures, since it is not considered as an element of vulnerability.

In table 3.4 we provide a synthesis of the second phase. In the column “Proposed values” we list, for the factors for which it was possible, on the basis of the responses provided by the panel, the values that we were able to suggest. On the column “weight proposed by the experts” we show the responses of the panel to the questionnaires of phase 2, and on the last column we provide the weights obtained from the data analysis, which will be the final values assigned to the factors.

Table 3.4: results for seismic vulnerability questionnaires in phase 2

		Proposed value	**Weight proposed by the experts**					**Weight**
	Category 1	0.45	0.6	0.4	0.45	0.55		0.45
Masonry	Height	[-]	0.2	0.2	0.165	0.2		0.2
	Year of construction	0.25	0.3	0.2	0.25	0.25		0.25
	Masonry typology	[-]	0.2	0.25	0.1925	0.35		0.25
	Foundation	0.05	0	0.05	0.05	0		0
	Roofing system	0.15	0.1	0.15	0.15	0.1		0.15
	Slab system	[-]	0.2	0.15	0.1925	0.1		0.15
Reinforced Concrete	Height	0.15	0.3	0.25	0.15	0.3		0.275
	Year of construction	0.25	0.5	0.25	0.25	0.5		0.35
	Type of resisting system	[-]	0.2	0.3	0.275	0.2		0.275
	Foundation	0.05	0	0.05	0.05	0		0
	Slab system	[-]	0	0.15	0.275	0		0.1

		Proposed value	**Weight proposed by the experts**					**Weight**
	Category 2	0.25	0.25	0.2	0.25	0.3		0.25
Masonry	Plan configuration	0.4	0.4	0.3	0.4	0.4		0.4
	Configuration in elevation	0.5	0.5	0.5	0.5	0.4		0.5
	Spacing between masonry	0.1	0.1	0.2	0.1	0.2		0.1
Reinforced Concrete	Plan configuration	[-]	0.4	0.3	0.35	0.3		0.35
	Configuration in elevation	[-]	0.5	0.5	0.35	0.2		0.45
	Infill distribution	[-]	0.1	0.2	0.3	0.5		0.2

		Proposed value	Weight proposed by the experts					Weight
Masonry and Reinforced Concrete	Category 3	0.3	0.15	0.4	0.3	0.15		0.3
	Seismic joints	0.19	0	0.25	0.19	0.175		0.2
	Seismic interventions	0.3	0	0.25	0.3	0.4		0.3
	Architectural components	0.15	0.2	0.125	0.15	0.075		0.15
	Plants	0.1	0	0.125	0.1	0.075		0.1
	State of maintenance	0.26	0.8	0.25	0.26	0.275		0.25

One expert, we'll call him X, has not provided weights, but stated that he finds himself generally in agreement with the values proposed after the phase 1 and with the opinion of the other experts. For this reason, we will evaluate the weights according to the values provided by the other experts and we'll assume that the expert X agrees (we left a blank column for him).

It is noticeable the opinion regarding the foundations for both reinforced concrete and masonry structures. In fact, it was considered as an extremely low or null factor of vulnerability, so that we choose to remove this factor from the list of factors for seismic vulnerability. The reason of this choice is that, if properly designed, shallow or deep foundations both provide good support to the structure, and the choice between one of the two typologies of foundations depends mainly on the soil type and not on seismic performance. For this reason, we can conclude that the typology of foundation is not an element of seismic vulnerability. A more accurate analysis could consider if foundations are properly designed based on the soil typology and the continuity, in terms of stiffness and strength, between the foundations and the structure.

3.3.2. Results of questionnaires on flood risk

The following steps were followed when drafting the phase 2 flood vulnerability questionnaires:

- From the analysis of the results of the phase 1 questionnaires, a value was deduced for each factor to be proposed as the one that agreed with the greatest number of opinions;
- Customised questionnaires were drawn up. The experts were asked to review their opinion on the factors for which they had provided values that disagreed with those proposed. Comments supporting the proposed values were also provided in the customised questionnaires, so that the experts had all the elements to reason about the opinion expressed by the other experts.
- Finally, the results were summarised, according to the same criterion used in phase 1, in order to obtain the final weights of the flood vulnerability factors.

For the sake of synthesis, we omitted the value of the mode and maximum deviation.

As we can see, three of the six experts on the panel in the second phase fully agreed with the weights we proposed at the end of phase 1. This result is very important as it tells us that the proposed weights are reasonable on the whole and indeed largely reflect the panel's opinion.

The third expert suggested increasing the values of the factors "building materials" and "type of heating system". Unfortunately, he did not suggest a reduction in the weights of the other factors, thus not fulfilling the requirement that the sum of the weights of the factors within a category must equal 1.

The fifth expert suggested slightly changing the weights of categories 2 and 3 in favour of the second. In addition, he suggested that the factors 'location of the plumbing system' and 'type of heating system' be given the same weight, as they may suffer similar contamination effects. However, the proposed weights remain similar.

The last expert suggested some modifications, in particular he suggested to increase the weight of category 1, and some minor changes in the values of the factors. Nevertheless, the sum of the weights he proposed is not unitary, so it was not possible to consider those values as applicable in the evaluation of the final weight. In any case we considered his general suggestions in increasing or decreasing some of the weights.

Since the concordance on weights was generally toward higher values for category 1, the sum of the weights is not unitary, but is 1.21. To solve this problem, we have

normalized the values of all factors to 1, so that the conceptual basis behind the weights are respected, as well as the constrain of unitary sum.
In table 3.5 for the category 1 in the column "weight" we will show the weight obtained for the analysis of answers | the normalized value.

Table 3.5: results for flood vulnerability questionnaires in phase 2

	Proposed value	**Weight proposed by the experts**						**Weight**	
Category 1	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0,3	
Year	0.07	0.07	0.07	0.07	0.07	0.07	0.05	0.07	0.06
residential typology	0.1	0.1	0.1	0.1	0.1	0.1	0.15	0.1	0.08
construction material	0.14	0.14	0.14	0.35	0.14	0.14	0.14	0.35	0.29
external walls cladding	0.14	0.14	0.14	0.14	0.14	0.14	0.2	0.15	0.12
interior walls material	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.1
internal walls cladding	0.21	0.21	0.21	0.21	0.21	0.21	0.15	0.20	0.17
floor material	0.22	0.22	0.22	0.22	0.22	0.22	0.15	0.22	0.18
	Proposed value	**Weight proposed by the experts**						**Weight**	
Category 2	0.45	0.45	0.45	0.45	0.45	0.5	0.45	0.45	
Number of floors	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Presence of basement floor	0.25	0.25	0.25	0.25	0.25	0.25	0.15	0.25	
Ground floor elevation	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
Floodable floors opening	0.14	0.14	0.14	0.14	0.14	0.14	0.2	0.14	
Presence of check valves	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	
Floodproofing measures	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	
	Proposed value	**Weight proposed by the experts**						**Weight**	
Category 3	0.25	0.25	0.25	0.25	0.25	0.2	0.25	0.25	
electric plant position	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
plumbing plant position	0.15	0.15	0.15	0.15	0.15	0.175	0.15	0.15	
thermal plant position	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
thermal plant typology	0.2	0.2	0.2	0.35	0.2	0.175	0.2	0.2	
A/C plant position	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	
emission terminals	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	

4 Expected annual loss

4.1. EAL as a weight for vulnerability

Having determined the seismic, flooding and energy efficiency vulnerability indices, the last step to obtain the integrated vulnerability is to determine a method to combine the individual vulnerabilities.

Since we are interested in obtaining an integrated vulnerability index, the use of combination factors associated with the local hazard is ruled out, since the result would no longer be a vulnerability but a risk (except for the exposure factor) and, for the same reason, the risk level cannot be used to combine vulnerabilities.

A combination term must be used, that has as meaning the mutual weight that the three vulnerability classes have among them, in terms of the building's response to an adverse event.

We have chosen to combine the three vulnerability classes according to the average damage that a building suffers if subjected to the given event (e.g. a flood or an earthquake) or the economic loss an owner suffers if not energy efficiency measures are adopted. In the following, both are referred to as annual economic loss. This choice is justified by the fact that vulnerability is the tendency of a building to suffer a damage, hence the more consistent way to combine vulnerabilities is by the expected loss per year.

The annual economic loss will be assessed for each risk class, as we will see in detail later in this chapter, and the ratio of the economic loss of a hazard types to the total loss (sum of the losses of the three hazard types) will give rise to the factor (C_x) to be used in the linear combination that returns the value of the integrated vulnerability V_{int} (Formula 4.1).

$$C_{seismic} = \frac{EAL_{seismic}}{EAL_{tot}}$$

$$C_{flood} = \frac{EAL_{flood}}{EAL_{tot}}$$

$$C_{seismic} = \frac{EAL_{seismic}}{EAL_{tot}} \qquad (4.1)$$

$$EAL_{tot} = EAL_{seismic} + EAL_{flood} + EAL_{energy}$$

$$V_{int} = C_{seismic} \times V_{seismic} + C_{flood} \times V_{flood} + C_{energy} \times V_{energy}$$

The notion of loss in general contains all losses, not only structural losses, but also losses in terms of human life, cultural heritage, etc. However, it is not possible to quantify human lives or the loss of cultural heritage in economic terms, so in the following when we talk about loss we will only refer to damage to buildings, to structural and non-structural elements, calculated for each hazard type.

Loss can be calculated with different levels of precision. One can either assess the average loss on a single building if one has sufficient information about hazard and exposure for all the risk types considered, or one can choose, due to the absence of detailed information or for practical reasons related to the numerosity of the sample of buildings under examination, to assess the loss at the provincial, regional or national level. In this case, approximate methods are used, which increases uncertainty but simplify the calculations (less information is required).

In our case, we chose to evaluate the expected annual loss at the provincial level, i.e. in the provinces of Bergamo and Varese, that are taken as reference as the ones where pilot buildings are located (Chapter 5).

The important thing, when choosing the scale at which the loss is calculated, is to maintain consistency of detail between the expected annual losses related to individual vulnerabilities. It would not make sense to weight vulnerabilities by considering for one risk type the loss calculated in detail at the building scale and for another class a loss assessed at the national scale.
Therefore, even one of the combination values cannot be determined with a certain level of detail, the most consistent choice is to broaden the level of detail and use the least detailed loss data for all risk classes.

In our analysis, for example, we had sufficient data to assess the loss at the individual building level for the flood and energy risk classes. However, it was not possible to assess the loss at the building level for the seismic risk class, since for reinforced concrete buildings one would have to assess the vulnerability class using a conventional method (Chapter 4.2.1) and this requires detailed information on the structures which was not in our possession. We therefore chose, for all three risk classes, to evaluate the expected annual loss at the provincial level.

4.2. Definition of EAL for each class of risk

4.2.1. Seismic EAL

The expected annual loss due to a seismic event is calculated using the Average Annual Loss (in Italian Perdita Annuale Media, PAM) [24].

The PAM quantifies the economic losses associated with damage to structural and non-structural elements, and refers to the reconstruction cost (CR) of the building without its contents.

The PAM parameter can therefore be assimilated to the cost of repairing the damage produced by the seismic events that will occur during the life of the building, apportioned annually and expressed as a percentage of the reconstruction cost, and is calculated by considering the area subtended by the curve representing the direct economic losses, as a function of the average annual frequency of exceedance (equal to the inverse of the average return period) of the events that cause the structure to reach a limit state. The smaller the area subtended by this curve, the lower the expected average annual loss. [24]

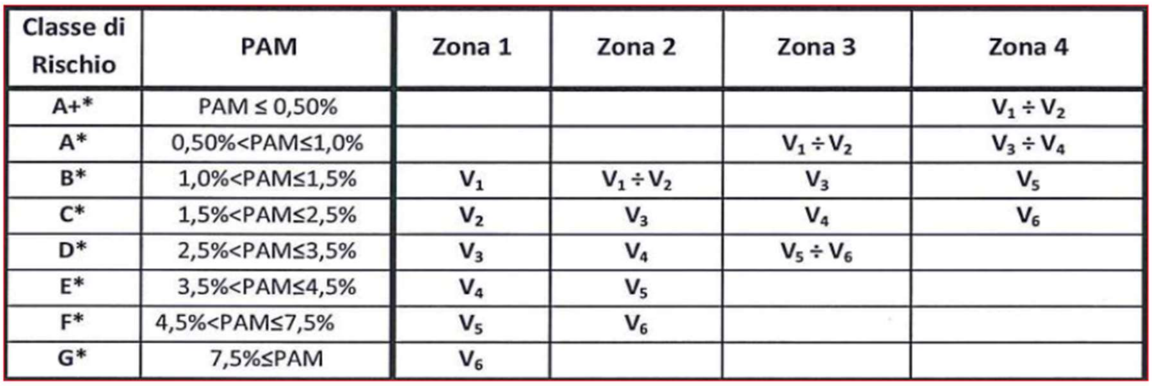
At the level of the individual building, the PAM class is determined by evaluating the vulnerability class of the building and combining this information with the seismic zone where the building is located, according to Table 4.1.
The vulnerability should be assessed by means of the conventional method, which compared the PGA of the expected earthquake with the PGA associated with the fist damage of the building. However, also a simplified method can be used, only for masonry structures, which is based on the European Macroseismic Scale EMS.

In our case we are interested in assessing the loss at a provincial level of detail, so we will disregard the evaluation of the building's vulnerability and only consider the seismic zone.
In particular, the municipality of Bergamo is classified as seismic zone 3, while the municipality of Varese is classified as zone 4. From table 4.1 we can see how in zone 3 the PAM class can vary, depending on the vulnerability of the building, from class A* to D*, while in zone 4 it ranges from A+* to C*.

In terms of economic loss, this means that:

- In zone 3 (Bergamo), a building with minimum vulnerability will have a loss of 0,5% and a building with maximum vulnerability will have a loss of 3,5 percentage points on the reconstruction cost, on average 2 percentage points;
- In zone 4 (Varese), between a building with minimum vulnerability and a building with maximum vulnerability there will be a loss of 2.5 percentage points on the reconstruction cost, on average 1.25 percentage points.

Table 4.1: PAM class assigned according to the vulnerability class assigned to the building and the seismic zone in which it is located [24].



Classe di Rischio	PAM	Zona 1	Zona 2	Zona 3	Zona 4
A+*	PAM ≤ 0,50%				$V_1 \div V_2$
A*	0,50%<PAM≤1,0%			$V_1 \div V_2$	$V_3 \div V_4$
B*	1,0%<PAM≤1,5%	V_1	$V_1 \div V_2$	V_3	V_5
C*	1,5%<PAM≤2,5%	V_2	V_3	V_4	V_6
D*	2,5%<PAM≤3,5%	V_3	V_4	$V_5 \div V_6$	
E*	3,5%<PAM≤4,5%	V_4	V_5		
F*	4,5%<PAM≤7,5%	V_5	V_6		
G*	7,5%≤PAM	V_6			

In order to determine the expected average loss, it is therefore only necessary to define what the reconstruction cost is.
The cost of reconstruction varies depending on the square footage to be built and the building typology. However, an estimate can be made without considering the cost of the land (in the case of post-earthquake reconstruction, the land will not be purchased). In northern Italy, where construction costs are higher, a 100 m^2 house costs between 80 000€ to 270 000€, depending on the type of house, equivalent to 800-2700€/m^2. For a two-family house, construction costs are around 1200-2200€/m^2. Based on these figures, we can estimate a construction cost of 1200 €/m^2, which corresponds to an intermediate value for detached houses and low for semi-detached houses. [48] We can therefore quantify the expected annual loss:

- In seismic zone 3 (Bergamo), an average annual loss of 24 €/m^2;
- In seismic zone 4 (Varese), an average annual loss of 15 €/m^2.

4.2.2. Flood EAL

The expected annual loss is obtained by performing the integral of the Damage-Probability of occurrence curve. To determine the expected annual loss due to the occurrence of a flood, we chose to exploit the damage curves implemented within the MOVIDA project. [25]

First, we took the hazard maps of 5 significant floodable areas inside the Po district, for 3 different return period, associated with a probability of occurrence low (500 years), medium (200 year) and high (50 years), so we had 15 datasets, five for each probability of occurrence.
The data came from an analysis carried out by the Po river district authority, where they mosaicked the five regions of the Po basin (Garza, Mella, Parma, Torino, Adda)

in areas of different extension (from 1 to 25 m^2) and in each portion the water height was calculated for the different probabilities of occurrence.

The data in each dataset where collected in order to obtain only three datasets for the Po basin, one for each probability of occurrence (Table 4.2). We paid attention to multiply the cumulative frequency of each dataset for the area in which the region was mosaicked, in order to have comparable data. Finally, we took the fractile 0.5 as the mean value, for each probability of occurrence, to be used in the next step. Although we are evaluating the losses at the provincial level, in this case we can assume the same value for both municipalities of Bergamo and Varese, since they are both located within the Po flood basin.

Table 4.2: Definition of a unique dataset for the Po basin (example for high probability of occurrence)

	Garza	Mella	Parma	Torino	Adda	Po Basin		
Height [m]	cum freq	cum freq	cum freq	cum freq	cum freq	Height [m]	cum freq	fractile [%]
0,01	1616	48100	516100	38175	30316	0,01	634307	1,27
0,02	4587	79975	843175	79950	58600	0,02	1066287	2,14
0,03	7724	117750	1155325	120800	89764	0,03	1491363	2,99
0,04	10067	153775	1464150	159600	124208	0,04	1911800	3,83
0,05	12512	188900	1777100	204000	157720	0,05	2340232	4,69
0,06	14838	220225	2090625	246425	196880	0,06	2768993	5,55
0,07	17015	251900	2411425	289125	238284	0,07	3207749	6,43
0,08	19023	281775	2747800	335825	277436	0,08	3661859	7,34
0,09	20861	311025	3103125	383700	316672	0,09	4135383	8,29
0,10	22716	337825	3461350	429350	357776	0,1	4609017	9,24
0,20	38865	588500	7185000	899150	743352	0,2	9454867	18,95
0,30	54038	821900	10230925,00	1399775	1106756	0,3	13613394	27,28
0,40	62837	1028525	12091550,00	1909875	1463892	0,4	16556679	33,18
0,50	69919	1219375	13385150,00	2409525	1835660	0,5	18919629	37,92
0,60	76104	1401550	14374675,00	2892700	2227284	0,6	20972313	42,03
0,70	81360	1583475	15245775,00	3328825	2639344	0,7	22878779	45,85
0,80	90953	1741425	15964550,00	3721975	3076912	0,8	24595815	49,30
0,90	101835	1890575	16716525,00	4077200	3525828	0,8000014		50,00
1,00	109807	2028800	17561450,00	4414975	3938848	0,9	26311963	52,73
TOT	208180	3078125	28825500,00	10130750	7652440	1	49894995	100
						TOT	49894995	

This was repeated for the three probabilities of occurrence low (T=500), medium (T=200) and high (T=50), and the following height values were obtained:

H(T=500) = 0.39
H(T=200) = 0.3
H(T=50) = 0.8

Normally, we would expect that as the probability of occurrence increase (frequent events) the water level decreases, since it is a general agreement that frequent events have moderate intensity, while infrequent events have higher intensity. Nevertheless, we obtained an opposite trend. This can be explained as follows: We are considering a mean value among five floodable areas of the Po district. For high probability events, the area subject to flood is near the river, with a certain water height.

If we take a low probability event, the area interested by the flood will be much larger than the area subjected to an high probability event. Now, the maximum water height of the low probability event will be larger than the one of the high probability event, but performing a mean among all the height in the area interested by the flood it is possible, as in this case, that the mean for the low probability event comes out to be lower than the mean height for the high probability event

Next, we took the damage curves defined in the MOVIDA project [25] and, at the heights determined before, we found the damage associated with each reference period.

In the MOVIDA project mentioned above, 3 models are proposed to assess the damage of residential buildings: the model proposed by Carisi et al, that of Arrighi et al, and the simple-INSYDE model.

We have chosen not to use the simple-INSYDE model because it assesses the relative damage of the individual building and requires specific assessments of the structure, while in our case we are assessing damage at a provincial scale and therefore this model is not appropriate.

The damage will therefore be given by the average between the damage obtained from Carisi et al's model (equation 4.2) and the damage obtained from Arrighi et al's model (equation 4.3), of which we will consider the model for buildings with basements since all the buildings we analysed in the case studies (Chapter 5) have basements (Figure 4.2).

$$d_{Carisi\ et\ al} = 0.13 \times \sqrt{h} \tag{4.2}$$

$$d_{Arrighi\ et\ al} = \begin{cases} 6 & h < 0{,}25m \\ 52 \times h - 7 & 0{,}25m \leq h < 1{,}5m \\ 17.5 \times h + 38.75 & 1{,}5m \leq h \leq 3{,}5m \end{cases} \qquad (4.3)$$

Arrighi et al's relative damage curve gives a percentage damage value, which reaches 100% at a height of 3.5 m corresponding to the first floor. The damage calculated is therefore not relative to the whole exposed area of the building, but only to the exposed area on the first floor, ground floor and basement (Figure 4.1). The absolute damage is given by the following equation 4.3:

$$\boldsymbol{D} = d \times A \times C \qquad (4.3)$$

d is the relative damage (in percent);
A is the plan area of the building
C is the restoration cost, considered within MOVIDA to be equal to the 65% of the cost of reconstruction.

Carisi et al's relative damage curve, on the other hand, considers damage relative to the economic value of the number of floodable floors, so the damage is given by equation 4.4:

$$\boldsymbol{D} = d \times E \qquad (4.4)$$

d is the relative damage;
E is the economic value of the individual building, evaluated as the number of floodable floors (n), in our case is always 1 time the plan area of the building (A).

The economic value of the building will be assessed in terms of the reconstruction cost of 1200 €/m^2 (Chapter 4.2.1). Therefore:

Arrighi et al →$D = \left(\frac{d}{100}\right) \times 1200 \times 0.65 \left[\frac{€}{m^2}\right]$
Carisi et al → $D = d \times 1200 \left[\frac{€}{m^2}\right]$

Finally, we constructed the damage curve as a function of the probability of occurrence, the integral of which returns the annual economic loss due to a flood event.

We clarify that the calculated loss is annual since it is calculated as the integral of the Damage-Probability curve. The probability of occurrence of an event represents the probability that in one year, an event with a certain intensity (as a function of flood height) will occur. Therefore, the notion of annual damage is intrinsic to the notion of probability of occurrence.

The D-P curve is obtained by taking as abscissae the values of the probabilities of occurrence (1/T) associated with the three return times of 500, 200 and 50 years, and as ordinates the average damage values obtained in the previous step (Figure 4.2).

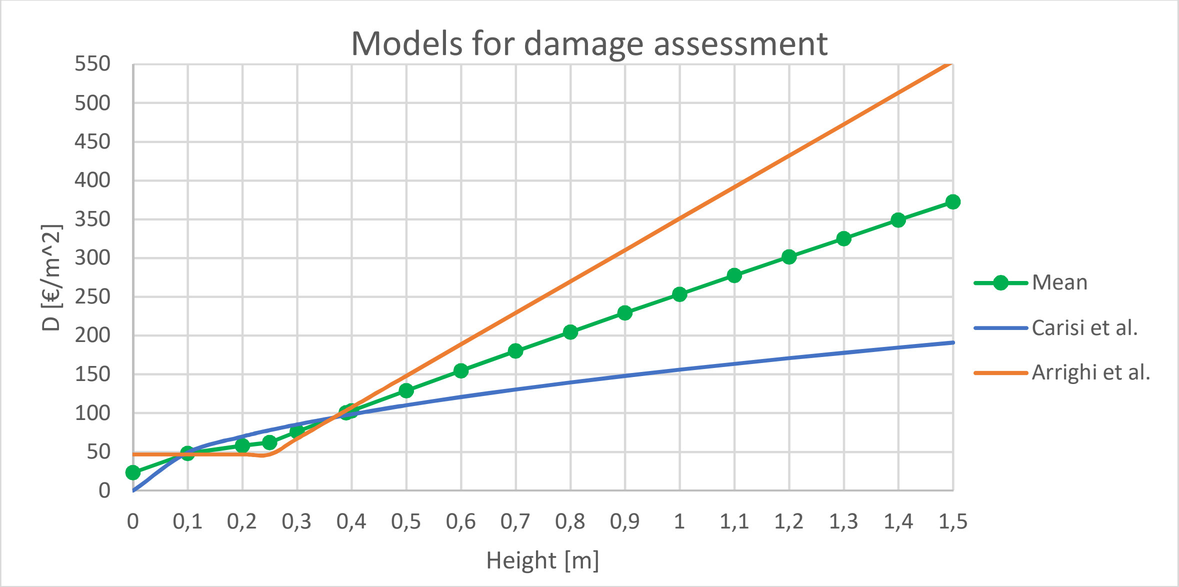


Figure 4.1: Carisi et al and Arrighi et al models of damage and mean damage

The integral of the curve returns the expected average damage, and can be evaluated by calculating the area subtended by the curve. In order to compute the integral, we have considered as 5 years, corresponding to a probability of 0.2, the return period of an event causing null damage.

In the following, the area subtended to the damage curve is computed and the integral comes out to be equal to 19.4 €/m^{2}year:

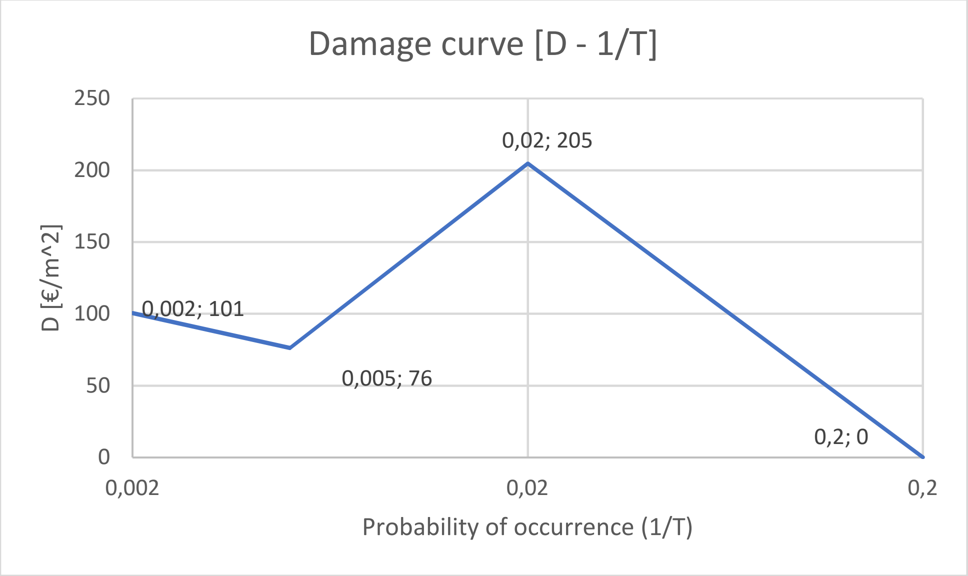


Figure 4.2: Damage curve

4.2.3. Energetic EAL

To determine the expected annual loss related to a lack of energy efficiency, the energy performance index ($EP_{gl,nren,ref,standard}$) was used.

The energy performance index indicates how much energy is consumed to ensure proper comfort conditions and considers the non-renewable primary energy demand for winter and summer air conditioning, domestic hot water production and ventilation (DM 26/06/2015 [49]) and is measured in kWh/m^2 per year.

This Index is particularly important when assessing the energy efficiency of buildings, since with the Ministerial Decree of 26/06/2015, the new Energy Performance Certificate bases the classification of buildings no longer on absolute consumption, but on the ratio between total consumption and the overall primary energy from non-renewable sources of the reference building, $EP_{gl,nren,ref,standard}$ (Figure 4.3).

To determine what the average loss is, we exploit the statistical data relating to the Lombardy region. [50] We have downloaded the data relating to the energy performance index as a function of energy class, for residential buildings (E1.1 dwellings used as residences with continuous character, E1.2 dwellings used as residences with occasional character) in the provinces of Bergamo and Varese (Table 4.3).

	Classe A4	≤ 0,40 $EP_{gl,nr,Lst(2019/21)}$
0,40 $EP_{gl,nr,Lst\ (2019/21)}$ <	Classe A3	≤ 0,60 $EP_{gl,nr,Lst(2019/21)}$
0,60 $EP_{gl,nr,Lst(2019/21)}$ <	Classe A2	≤ 0,80 $EP_{gl,nr,Lst(2019/21)}$
0,80 $EP_{gl,nr,Lst(2019/21)}$ <	Classe A1	≤ 1,00 $EP_{gl,nr,Lst(2019/21)}$
1,00 $EP_{gl,nr,Lst\ (2019/21)}$ <	Classe B	≤ 1,20 $EP_{gl,nr,Lst(2019/21)}$
1,20 $EP_{gl,nr,Lst(2019/21)}$ <	Classe C	≤ 1,50 $EP_{gl,nr,Lst(2019/21)}$
1,50 $EP_{gl,nr,Lst\ (2019/21)}$ <	Classe D	≤ 2,00 $EP_{gl,nr,Lst(2019/21)}$
2,00 $EP_{gl,nr,Lst\ (2019/21)}$ <	Classe E	≤ 2,60 $EP_{gl,nr,Lst(2019/21)}$
2,60 $EP_{gl,nr,Lst\ (2019/21)}$ <	Classe F	≤ 3,50 $EP_{gl,nr,Lst(2019/21)}$
	Classe G	> 3,50 $EP_{gl,nr,Lst(2019/21)}$

Figure 4.3: Energy Performance Certificate classification

The average annual loss is calculated as the difference, in terms of $EP_{gl,nren,ref,standard}$, between an average energy class situation (we considered the average between energy classes B and C) and the top performing situation (class A4).

The difference in $EP_{gl,nren,ref,standard}$ thus found, multiplied by the cost per kWh of primary energy gives the expected annual loss.

In order to evaluate the cost of primary energy, we made the following assumptions:

- If the heating system is based on a gas boiler (which is the most common situation in the reference contexts), assuming a natural gas cost of about 0.9 €/m^3 (in the first trimester of 2022 the cost was about 0.89€/m^3 [51]), the specific cost of non-renewable primary energy is about 0.084 €/kWh. 1 m^3 of gas is in fact about 10.69 kWh of non-renewable primary energy. [52]
- If the heating system is a vapour compression heat pump, with an electricity cost of 0.355 €/kWh [53] we get about 0.16 €/kWh of non-renewable primary energy. In fact, 1 kWh of electricity from the grid corresponds to 1.95 kWh of non-renewable primary energy. It must be noted that, although this cost in higher than that obtained with natural gas, the non-renewable primary energy required by the building will be less than in the case with a gas boiler because the heat pump is more efficient.

Since currently the most common systems are still gas systems, it makes sense to consider 90% of systems based on gas boiler, and 10% on heat pumps. In this way we have a cost of about 0.10 €/kWh. Obviously, the costs considered are 'pre-crisis'.

Considering that the cost of primary energy can be assumed to be 0.10 €/kWh, for the provinces of Bergamo and Varese we obtain the following average annual loss values:

$$\begin{aligned}\mathrm{EAL}_{\mathrm{Bergamo}} &= \Delta\mathrm{EPgl} \times \text{energy cost} = (188.41 - 96.19)\,\frac{\mathrm{kWh}}{\mathrm{m^2year}} \times 0.10\,\frac{€}{\mathrm{kWh}} \\ &= 9.22\,\frac{€}{\mathrm{m^2year}} \\ \mathrm{EAL}_{\mathrm{Varese}} &= \Delta\mathrm{EPgl} \times \text{energy cost} = (342.81 - 192.61)\,\frac{\mathrm{kWh}}{\mathrm{m^2year}} \times 0.10\,\frac{€}{\mathrm{kWh}} \\ &= 15.02\ €/(\mathrm{m^2year})\end{aligned}$$

Table 4.3: $EP_{gl,nren,ref,standard}$ for the cities of Bergamo and Varese

	BERGAMO			VARESE		
ENERGETIC CLASS	EP_{gl}(E1.1)	EP_{gl}(E1.2)	$EP_{gl,tot}$ (E1+E2)	EP_{gl}(E1.1)	EP_{gl}(E1.2)	$EP_{gl,tot}$ (E1+E2)
A4	87,46	104,92	96,19	104,92	87,69	192,61
A3	117,04	144,16	130,60	144,16	139,12	283,28
A2	124,18	111,55	117,87	111,55	153,76	265,31
A1	141,23	165,26	153,25	165,26	187,44	352,70
B	179,16	153,09	166,12	153,09	170,49	323,58
Mean			188,41			342,81
C	233,81	187,57	210,69	187,57	174,47	362,03
D	241,97	279,24	260,60	279,24	353,20	632,44
E	236,89	258,94	247,91	258,94	283,18	542,12
F	251,18	290,49	270,83	290,49	290,50	580,99
G	363,22	464,39	413,81	464,39	458,89	923,28

4.3. Evaluation of the combination factors

Having determined, for the provinces of Bergamo and Varese, the expected annual losses for each risk class, we are now able to calculate the multiplicative coefficients that we will use for the combination of the vulnerability indices, to obtain the integrated vulnerability.

It is important to recall that the term used for the combination must fulfil the criterion of being possible to be assessed, with more or less detail, in different locations and according to the characteristics of the building, or building unit under consideration. In Table 4.4 we report, for the two provinces of the Lombardy region, the values of the losses and the relative combination coefficients.

Table 4.4: Expected Annual Losses and Combination Coefficients

[€/m^{2}year]	**EAL$_{seismic}$**	**EAL$_{flood}$**	**EAL$_{energy}$**	**EAL$_{tot}$**
Bergamo	24	19.4	9.22	52.62
Varese	15	19.4	15.02	49.42
[%]	**C$_{seismi}$**	**C$_{flood}$**	**C$_{energy}$**	
Bergamo	45.61	36.87	17.52	
Varese	30.35	39.26	30.39	

From these results, we can state the following:

- In general, the costs associated to the lack of energy efficiency are lower or similar with respect to seismic or flood damage. This can be explained considering that in the case of energy efficiency, the loss is related to a higher cost for energy, but do not imply structural and/or non-structural damages. In fact, we are only considering the aspect related to energy costs, neglecting external impacts such as environmental impact due to emissions.
- The costs related to flood or seismic risks are more or less similar. However, we have to underline that both locations are characterised by a low or very low seismic risk while being subjected to a significant flooding risk. This is due to the fact that the damages and monetary losses induced by the occurrence of an earthquake are typically higher than the ones caused by a flood. Hence, we can understand that, in terms of monetary losses, a small earthquake is equivalent to a significant flood, a fact that stresses the importance of building earthquake-resisting structures in the totality of the national territory and not only in high risk regions.

5 Integrated vulnerability index

5.1. Final overview of the method applied

To conclude the discussion of the developed methodology and before going on to analyse the case studies, we report in a unified way the results obtained so far. Our methodology proposes a new way of determining the integrated vulnerability of a building with respect to flood and seismic risk and energy efficiency. To do this, vulnerability indices are combined according to the EAL corresponding to each risk class. From the analysis we conducted (Chapter 4), the combination factors result as follows (Table 5.1).

Table 5.1: Combination coefficients

[%]	C_{seismi}	C_{flood}	C_{energy}
Bergamo	45.61	36.87	17.52
Varese	30.3	39.26	30.39

The individual vulnerabilities will be determined by identifying, for each factor, what value that factor assumes for the building under consideration, and the corresponding score.

The scores assigned to the values and the values themselves have been determined on the basis of our technical knowledge and the literature (Chapter 2). The weight of the factors will be given by the weight assigned to the individual factor multiplied by the weight of the corresponding category. These weights were defined through the application of a two-stage Delphi methodology (Chapter 3).

With all the data collected during our research, we were able to build the vulnerability indices and to evaluate the combination factors, so to apply the methodology to real cases. Below (Table 5.2, 5.3, 5.4) we report these results for the three risk types.

Table 5.2: Weights and Scores for Seismic Vulnerability Index

Category 1								0.45
RC	**weight**	**Scores**		**MASONRY**	**weight**	**scores**		
Height	0.275	1-2 floors	0	Height	0.2	1-2 floors	0	
		3-4 floors	0.2			3-4 floors	0.2	
		5-6 floors	0.6			5-6 floors	0.6	
		>7 floors	1			>7 floors	1	
Year of construction	0.35	Post 2009	0.1	Year of construction	0.25	Post 2009	0.1	
		1975-2009	0.7			1975-2009	0.7	
		Before 1975	1			Before 1975	1	
Type of resisting system	0.275	Frame, coupled walls, mixed.	0	Masonry typology	0.25	Reinforced masonry, reinforced masonry with capacity design, confined masonry with capacity design	0.66	
		Unbonded or inverted pendulum framed single-story walls	0.33					
		Torsionally deformable structures	0.66			Ordinary or confined	1	
		Reverse pendulum structures.	1					
Slab system	0.1	Rigid slab	0	Slab system	0.15	Rigid slab	0	
		Semi-rigid slab	0.5			Semi-rigid slab	0.5	
		Flexible slab	1			Flexible slab	1	
				Roofing system	0.15	Non-pushing LM	0	
						Non-pushing H / pushing L	0.5	
						Pushing MH	1	

<table>
<tr><th colspan="8">Category 2</th><th>0.25</th></tr>
<tr><th>RC</th><th>weight</th><th colspan="2">scores</th><th>MASONRY</th><th>weight</th><th colspan="2">Scores</th><th></th></tr>
<tr><td rowspan="2">Configuration in plan</td><td rowspan="2">0.35</td><td>Regular</td><td>0</td><td rowspan="2">Configuration in plan</td><td rowspan="2">0.4</td><td>Regular</td><td>0</td><td></td></tr>
<tr><td>Non-regular</td><td>1</td><td>Non-regular</td><td>1</td><td></td></tr>
<tr><td rowspan="2">Configuration in elevation</td><td rowspan="2">0.45</td><td>Regular</td><td>0</td><td rowspan="2">Configuration in elevation</td><td rowspan="2">0.5</td><td>Regular</td><td>0</td><td></td></tr>
<tr><td>Non-regular</td><td>1</td><td>Non-regular</td><td>1</td><td></td></tr>
<tr><td rowspan="3">Infill distribution</td><td rowspan="3">0.2</td><td>Absent or regular</td><td>0</td><td rowspan="3">Maximum spacing</td><td rowspan="3">0.1</td><td>< 5 m</td><td>0</td><td></td></tr>
<tr><td>Non-regular in plan or elevation</td><td>0.8</td><td></td><td></td><td></td></tr>
<tr><td>soft storey</td><td>1</td><td>> 5 m</td><td>1</td><td></td></tr>
</table>

Category 3

0.3

RC&MASONRY	weight	Scores	
Seismic joints	0.2	Present	0
		Absent	1
Seismic interventions	0.3		pre'03 | post'03
		Upgrading	0 | 0
		Improvement	0.33 | 0
		Local interventions	0.66 | 0
		No intervention	1 | 0
Architectural components	0.15	Floors	0.1
		Furniture, contents, false ceilings	0.4
		Tiles, windows, shutters	0.7
		projecting elements, masonry infills, cladding	1
Plant components	0.1	Accommodation defined at the design stage	0
		Facilities added later, no reduction of load-bearing capacity	0.5
		Facilities added later, reduction of load-bearing capacity	1
State of maintenance	0.25	Excellent	0
		Moderate	0.5
		Poor	1

Table 5.3: Weights and Scores for Flood Vulnerability Index

Category 1				0.3
	weight	Scores		
Residential type	0.06	Detached house	0.5	
		Semi-detached house	0.75	
		Apartment	1	
Year of construction	0.08	Post 2009	0.2	
		1975-2009	0.7	
		Before 1975	1	
Construction material	0.29	Reinforced Concrete	0.1	
		Mixed	0.2	
		Stone/masonry	0.4	
		Timber	1	
Exterior walls cladding	0.12	Stoneware	0.1	
		Bricks or exposed stones	0.25	
		Non-isolated plaster	0.8	
		Isolated plaster	1	
Interior walls material	0.1	RC/ glass block	0.2	
		Bricks	0.4	
		plasterboard /timber	1	
Interior wall cladding	0.17	Ceramic/washable plaster	0	
		Plaster	0.75	
		Paper/wood	1	
Floor material	0.18	Resin/cement/ceramic	0.2	
		Stone/PVC	0.6	
		Parquet/moquette	1	
Category 2				0.45
	weight	Scores		
Number of floors	0.05	More than 1	0.5	
		1	1	
Presence of basement floor	0.25	No	0	
		Yes	1	
Ground floor elevation	0.25	hg > h(P1)	0	0.2
		h(P2) < hg < h(P1)	0.33	
		h(P3) < hg < h(P2)	0.66	1
		hg < h(P3)	1	
Floodable floor opening	0.14	Absence of manholes and openings area < 30% total outdoor surface area	0	
		Absence of manholes and openings area > 30% total exterior surface area	0.4	
		Presence of manholes and openings area < 30% total exterior surface area	0.7	
		Presence of manholes and openings area > 30% total outdoor surface area	1	
Presence of check valves	0.12	Yes	0	
		No	1	

Floodproofing measures	0.19	Wetproofing and dryproofing measures	0	
		Wetproofing measures	0.4	
		Dryproofing measures	0.6	
		No	1	
Category 3				0.25
	weight	**Scores**		
Electrical system position	0.2	$hg > h(P1)$	0	0.2
		$h(P2) < hg < h(P1)$	0.33	
		$h(P3) < hg < h(P2)$	0.66	1
		$hg < h(P3)$	1	
Plumbing system position	0.15	$hg > h(P1)$	0	0.2
		$h(P2) < hg < h(P1)$	0.33	
		$h(P3) < hg < h(P2)$	0.66	1
		$hg < h(P3)$	1	
Thermal system position	0.2	$hg > h(P1)$	0	0.2
		$h(P2) < hg < h(P1)$	0.33	
		$h(P3) < hg < h(P2)$	0.66	1
		$hg < h(P3)$	1	
Heating system type	0.2	Centralized	1	
		Independent heating	0.75	
		District heating	0	
AC system position	0.15	$hg > h(P1)$	0	0.2
		$h(P2) < hg < h(P1)$	0.33	
		$h(P3) < hg < h(P2)$	0.66	1
		$hg < h(P3)$	1	
Emission terminals	0.1	Radiators	0.1	
		Radiant floor panels / thermal convectors	1	

Table 5.4: Weights and Scores for Energy Efficiency Index

Category 1				0.165
	weight	**Scores**		
n-er of floors	0.35	1-4 floors	0.5	
		> 4 floors	1	
Surface-to-volume ratio	0.25	S/V < 0,4	0	
		0,4 < S/V < 0,7	0.5	
		S/V > 0,7	1	
Windows-to-walls ratio	0.4	<15%	1	
		15-30%	0.5	
		30-50%	0	
		>50%	1	
Category 2				0.375
	weight	**Scores**		
Year of construction	0.25	Post 2015	0.2	
		2005-2015	0.4	
		1991-2005	0.6	
		1973-1991	0.8	
		Pre 1973	1	
External wall stratification	0.18	Massive insulated structure	0.2	0.2
		Light insulated structure	0.75	0.45
		Massive non-insulated structure	0.45	0.75
		Lightweight non-insulated structure	1	1
Stratification of slabs towards the outside or unheated rooms	0.1	Massive insulated structure	0.2	0.2
		Light insulated structure	0.75	0.45
		Massive non-insulated structure	0.45	0.75
		Lightweight non-insulated structure	1	1
External wall cladding	0.05	Clear cladding	0.2	1
		Dark cladding	1	0.2
Type of window frame	0.18	Thermal break frame and triple glazing	0	
		Thermal break frame and double glazing	0.5	
		Frame without thermal break and single glass	1	
Solar shading	0.15	Movable solar shading	0	
		Fixed solar shading	0.5	
		Absence of external solar shading on glazed surfaces	1	
Energy Performance Certificate	0.09	A4	0	
		A3-A2	0.1-0.2	
		A1-B	0.3-0.4	
		C-D	0.5-0.6	
		E-F	0.7-0.8	
		G o Absent	0.9-1	

Category 3			0.46
	weight	**Scores**	
Type of emission terminals	0.1	Radiant surfaces	0.2
		Fancoils or air terminals	0.6
		Radiators	1
Type of system regulation	0.1	On-off/thermostat	1
		Climate regulation	0
Type of DHW production system	0.15	Solar thermal system/heat pump	0
		Bolier powered by fossil fuels	0.7
		Electric boiler	1
Presence of installations powered by renewable resources	0.2	> 2 kW	0
		1-2 kW	0.4
		<1 kW	0.7
		No	1
Type of heating system	0.05	Centralized with thermoregulation/containment	0.2
		Autonomous	0.7
		Centralized without thermoregulation/contabilization	1
A/C system	0.14	Absent	0 | 0.2
		Centralized system	0.4
		Autonomous (split or similar)	1
Type of heat generating system	0.2	Heat pump / biomass system	0.2
		Hybrid system (boiler + heat pump) / district heating system	0.4
		Condensing boiler fired by fossil fuels	0.8
		Traditional boiler fired by fossil fuels	0,1
Presence of controlled mechanical ventilation system	0.06	Yes, with heat recovery	0
		Yes, without heat recovery	0.5
		No	1

5.2. Critical appraisal of the results obtained

The main element of the developed methodology is the possibility to study how the various factors influence the integrated vulnerability.

In the following, we will analyse the influence of factors on integrated vulnerability and individual vulnerabilities.

Factors common to more than one vulnerability index.

- Height is a factor common to all three types of risk we have analysed. For both seismic risk and energy efficiency, the lower the number of storeys, the lower the vulnerability. In the case of flood risk, on the other hand, there is a reduction in vulnerability for single-storey buildings. Although the height factor for flooding has a lower weight ($0.05 \cdot 0.45 = 0.0225$) than in the case of seismic

(0.275 · 0.45 = 0.124 or 0.2 · 0.45 = 0.9) and energy (0.135 · 0.165 = 0.022), we can say that the best case in terms of integrated vulnerability is for a 2-storey building, which falls in the minimum score for all three vulnerabilities. For existing buildings, this factor cannot be modified, but for new buildings, it can be considered good practice to design buildings with more than one storey but a reduced height.

- The year of construction is a factor common to all indices, and in each of them the older the building, the greater the vulnerability. This is an element of vulnerability on which no action can be taken.
- The construction material is an important factor influencing seismic vulnerability, flood vulnerability and to some extent energy efficiency. In the case of seismic vulnerability, masonry buildings perform less well than those made of reinforced concrete, and in the case of flood vulnerability, reinforced concrete buildings perform better than those made of other materials. As far as energy efficiency is concerned, there is no direct correlation between performance and building material, but rather with whether the external walls are massive and insulated, which is more the case for buildings constructed of reinforced concrete or wood than for buildings constructed with light non-insulated walls. Therefore, a general consideration is that, in order to reduce integrated vulnerability, the ideal is to construct buildings in reinforced concrete. It is not always possible to intervene on this structural aspect.
- The last element common to all vulnerability indices is the presence of installations. Although for all three hazards the presence, location and type of installations has an effect on vulnerability, the characteristics of the installations that affect individual vulnerabilities are different, so it is not possible to suggest one type or location of installations that affects the different indices. However, a good rule of action is to design the installations in such a way that they are not only efficient, but also that their location and presence does not decrease vulnerability to other risks. This is therefore something that can be worked on a lot, for example avoiding locations under floodable levels.

<u>Factors with greater weight in the definition of the indices.</u> The values of the weights we are going to quote will be the result between the weight of the factor and the weight of the corresponding category.

- Seismic vulnerability index. In category 1, for RC buildings, the factor with the greatest weight is the year of construction with 0.157. Second is the type of resistant system, which obtains less weight (0.124) since it is considered that all RC structures, if properly designed, are capable of providing a response to horizontal actions. Similarly, for masonry buildings, we find the year of construction and the type of masonry tied with 0.112. The latter factor is of fundamental importance in understanding and estimating the earthquake performance of a building. In category 2, for both RC and masonry buildings, the experts considered that the major contribution is provided by the elevation configuration, to which 0.112 and 0.125 is given, respectively. Second, for both building materials, is the configuration in plan, which still makes a significant contribution to vulnerability with 0.087 for RC and 0.1 for masonry, respectively. In category 3, there is no longer any distinction between the two types of construction materials. The factor offering the greatest contribution is the presence of earthquake-resistant interventions with a weight of 0.09. This is followed by the state of maintenance, with a weight of 0.075. Intervening on these factors alone, we act on 64.6% of the vulnerability with 6/12 of the vulnerability factors for reinforced concrete buildings, and on 61.5% of the vulnerability with 6/13 of the vulnerability factors for masonry buildings.

- Flood vulnerability index. In category 1, the factor with the highest weight is the building material, with 0.087, followed by the floor material, with 0.054. The reason for the higher weight of these elements is the fact that, in the event of a flood, load-bearing walls and floors are made of material which have a higher physical vulnerability toward water, and also, they require a greater economic effort to be replaced. In category 2, we find the factors of basement presence and ground floor height tied, with a weight of 0.112. Second to these is the presence of floodproofing measures, with a weight of 0.085. In category 3, we find the thermal, heating and electric plant position factors tied, with a weight of 0.05. The greater weight of the position of these plants compared to the others is that if damaged, these plants require a greater economic effort to replace, and in addition, the A/C plant is not always present and the plumbing plant tends to be damaged less.
  By acting on these main factors, 60.15% of the vulnerability with 8/19 of the vulnerability factors are addressed.
- Energy efficiency index. In category 1, the factor with the highest vulnerability is WWR, with 0.066. In category 2, the factor with the greatest weight is the year of construction, with 0.094. This is followed equally, with 0.067, by the factors external wall stratification and type of window frame, a result that suggests that the insulation of the dwelling against external agents (heat or cold) is of primary importance in the energy efficiency of a building. In category 3, we find equal, with a weight of 0.092, the factors of presence of renewable sources and type of heat generating system. It is followed, with a weight of 0.069, by the factor type of DHW production system. Intervening on these main factors, we act on 54.77% of the vulnerability with 7/18 of the vulnerability factors.

At the general level, the following observation must also be made: when there are common factors that have conflicting effects on more than one vulnerability index, the choice of the best factor value depends not only on the weight of the factor in the indices, but also on the combination factors of the indices in the integrated vulnerability, and thus on the corresponding losses.
An example is the case of the construction year factor.
As we have seen, this is a factor common to all three indices and is at the same time one of the factors with the greatest weight for seismic vulnerability and energy efficiency.
Let us assume that we have two identical RC buildings in the province of Bergamo, one built in 1970 and one built in 2010. Let us see how the integrated vulnerability varies just by changing one of the main factors.

Year of construction	Seismic Vulnerability	Flood Vulnerability	Energy efficiency
1970	1 × 0.35 × 0.45	1 × 0.08 × 0.3	1 × 0.25 × 0.375
2010	0.1 × 0.35 × 0.45	0.2 × 0.08 × 0.3	0.4 × 0.25 × 0.375
Difference	0.142	0.019	0.056

If we consider the combination factors of the single vulnerabilities with respect to the EAL computed for the province of Bergamo we obtain:

[Year]	$\mathbf{V}_{\mathbf{seismic}}$	$\mathbf{V}_{\mathbf{flood}}$	$\mathbf{V}_{\mathbf{energy}}$	**Overall improvement**
1970/2010	0.142 × 45.61	0.019 × 36.87	0.056 × 17.52	8.16 [%]

We achieved an increase of more than 8% by only changing the value of one factor that was important for two out of three indices.
Obviously, this is only a numerical example, since the year of construction cannot be changed, but it makes the idea we want to convey well, namely that by consciously working on the factors, benefits can be obtained for several vulnerabilities.

We can also note the influence that the combination coefficients had in the result. In fact, in itself, the factor weighted heavily in the seismic vulnerability index and this added up with the fact that seismic vulnerability has the greatest weight (45.61%) in integrated vulnerability. Therefore, of the 8% improvement in integrated vulnerability, about 6.5% comes from an improvement in seismic vulnerability.

We would also like to give the example of construction material and building type. This factor turns out to be common to the three vulnerabilities, although with the conceptual limitations expressed above with respect to energy efficiency, in fact for this index we consider the external walls stratification factor. It also turns out to be one of the factors with greater weight for both seismic and flooding vulnerability.

Let us assume that we have two identical buildings in the province of Bergamo, one built with a reinforced concrete wall structure and the other with ordinary masonry. Let us see how the integrated vulnerability varies.

Construction material	Seismic Vulnerability	Flood Vulnerability	Energy efficiency
RC wall	0 × 0.35 × 0.45	0.1 × 0.29 × 0.3	0.2 × 0.18 × 0.375
Ordinary masonry	1 × 0.25 × 0.45	0.4 × 0.29 × 0.3	0.45 × 0.18 × 0.375
Difference	0.112	0.026	0.017

If we consider the combination factors of the single vulnerabilities with respect to the EAL computed for the province of Bergamo we obtain:

[Material]	$V_{seismic}$	V_{flood}	V_{energy}	**Overall improvement**
RC/Mas	0.112 × 45.61	0.026 × 36.87	0.017 × 17.52	6.36 [%]

In this case, opting for a RC wall structure rather than light masonry results in a vulnerability improvement in the order of 6.3%. Of this, approximately 5.1% is due to the increase in seismic performance.
Therefore, it can be deduced that this choice is highly recommended in the case of a building located in areas where the loss of seismic vulnerability is preponderant compared to other vulnerabilities.
On the other hand, if the loss for the seismic vulnerability index is negligible, the choice of building material has little influence on the integrated vulnerability.

We can extend these examples to more general considerations. It can be argued that, when deciding which interventions should be implemented to improve the integrated vulnerability of a residential building, the best way is to reason comprehensively about both the weight of the factors within the individual vulnerabilities and the weight that the individual vulnerabilities have in the integrated vulnerability. In this way, one can understand which factors, if changed, have the greatest impact on the integrated vulnerability and opt for interventions that offer the greatest improvement with the least expense.

5.3. Application of case studies

In the following we will apply the methodology to two case studies. In the province of Varese, for the municipalities of Cugliate-Fabiasco, Cunardo and Marchirolo, we will apply the methodology to various existing buildings in order to determine which actions can be implemented to improve the integrated vulnerability of existing residential buildings. It will not be possible in this case to act on those factors that cannot be modified, such as the year of construction or the construction material.

In the case of Bergamo, on the other hand, we will apply the methodology to the case of an existing building that will be demolished and rebuilt. Therefore, all local conditions being equal, we want to quantify the improvement in vulnerability of the new project compared to the previous conditions.

In both cases, the informations have been collected during a campaign of in site inspections of the buildings, where we took advantage of inspection sheets (Appendix D) for seismic and flood-energy characterization of buildings.

Table 5.5 shows the final results of applying the methodology to all the cases examined. Details of the definition of the vulnerability indices can be found in Appendix C.

Table 5.5: Results of the application of the methodology to all case studies

		SEISMIC VULNERABILITY	$C_{seismic}$ [%]	FLOOD VULNERABILITY	C_{flood} [%]	ENERGY EFFICIENCY	C_{energy} [%]	INTEGRATED VULNERABILITY
Cugliate-Fabiasco	via Pagliolico 48	0,387	30,35	0,619	39,26	0,447	30,39	0,496
	Via Torino 61D	0,394	30,35	0,517	39,26	0,447	30,39	0,458
	Via S.Pietro 35B	0,307	30,35	0,659	39,26	0,383	30,39	0,468
Cunardo	Via Verdi 11	0,328	30,35	0,361	39,26	0,482	30,39	0,388
	Via Pradonico 7	0,623	30,35	0,552	39,26	0,627	30,39	0,596
	Via Prada 27	0,636	30,35	0,550	39,26	0,376	30,39	0,523
Marchirolo	Via Baraggia 31	0,307	30,35	0,559	39,26	0,520	30,39	0,471
	Via Statale 36	0,332	30,35	0,534	39,26	0,520	30,39	0,469
Bergamo	Bergamo Pre	0,695	45,61	0,599	36,87	0,686	17,52	0,658
	Bergamo Post	0,089	45,61	0,579	36,87	0,306	17,52	0,308

5.3.1. Application of the methodology to select appropriate interventions. Varese case studies.

As anticipated, for the province of Varese we want to apply the methodology to understand which actions are most convenient to put into practice to obtain the greatest increase in vulnerability with the lowest cost. As we can see from Table 5.5, the building with the lowest integrated vulnerability (V_{int} = 38.77 %) is Via Verdi 11, Cunardo, so we believe that it is not the best case to investigate. Instead, we will focus on the buildings located in Via Pradonico 7, Cunardo (V_{int} = 59.62 %), Via Pagliolico 48, Cugliate-Fabiasco (V_{int} = 49.6 %) and Via Baraggia 31, Marchirolo (V_{int} = 47.06 %), which are the dwellings with the highest vulnerability and therefore most in need of actions to reduce vulnerability.

The reader is invited to consider that from here on we will focus our discussion on specific, real buildings, so the conclusions we draw will be specific to those cases. Nevertheless, the methodology can be applied to any other residential building for which ad hoc results can be obtained.

In the following we will give a full description of the building located at Via Pradonico 7, so as to provide an example of what information is needed to define the vulnerability indices, and how to assign scores in the case where not all the necessary data is available or when a factor takes on a non-tabulated score (Chapter 2.3). Next, we report a table containing the vulnerability indices compiled for the three buildings under consideration.
Finally, by analysing the results obtained, we will be able to propose some actions to reduce the integrated vulnerability of the buildings studied.

<u>Via Pradonico 7, Cunardo, Varese.</u>

The building is a two-storey semi-detached house made of ordinary masonry without a basement, built in the early 1970s. Given the type of construction, it is assumed that the floors are semi-rigid, and we know that the ceiling is medium-heavy and pushing (pitched). From the visual analysis of the exterior, we can state that the building is regular in elevation, while in the absence of technical drawings it is not possible to define the plan configuration and the distance of the masonry, so an average value of 0.5 is associated with these factors. We know of the absence of seismic joints and seismic intervention, elements that greatly increase seismic vulnerability. Architectural components that can increase the risk of damage following an earthquake are tiles, windows and shutters. Some of the installations were built after the construction of the building, but in a way that does not reduce the load-bearing capacity of the walls in which they are placed. The state of maintenance is moderate.

The external walls are clad in light-coloured insulated plaster, while the internal brick walls are covered with plaster. The floors are ceramic. The plumbing system is not equipped with check valves and no floodproofing measures have been implemented. The height of the water depths for low, medium and high probability floods is not known. Therefore, we will refer to the height of the last known flood, which caused an external water height of 0.4m and an internal water height of 0.35m. The ground floor elevation is above 0.4m with the presence of manholes and an area of openings less than 30% of the total. The electrical system is below the flooded elevation while the height of the plumbing plant is unknown so the value of 0.5 will be adopted. The heating system is located above the flooded internal height, and there is no A/C system. The heating system is independent, with radiators as emission terminals.

From the analysis of the available photos, it was deduced that the S/V ratio is less than 0.4 and the WWR is less than 15%. The layering of the external walls and slabs to the outside or to unheated rooms is massive but not insulated. The windows have single glazing without thermal break, and there are no solar shadings. The energy classification is not present. The heating system is regulated by a thermostat and powered by fossil fuels, the DHW production system is powered by fossil fuels and there are solar panels (the power is not known so we assign a value of 0.4). There is no controlled mechanical ventilation system.

This is an example of the information needed to assess a building in terms of its integrated vulnerability to seismic, flood and energy efficiency risks. All this information was collected during the site survey phase prior to the definition of the vulnerability indices. During the surveys, in which we took advantage of the inspection sheets (Appendix D), not only we could gather the majority of informations on the buildings, but also this phase permitted us to acquire more knowledge about the issue of flood and seismic vulnerability and energy efficiency. On the basis of the in-field experience, we could create the indices of vulnerability applied in the methodology. Since, analysing the data gathered during the inspections, we found out that some aspects where important and not present in the inspection sheets, this is why we do not always have all the necessary information available. Hence, the inspection phase can be considered as a part of the desk research, since the information gathered in this phase served to complete the notions that led to the definition of the indices.

The same procedure was followed for the other locations and the results can be found in table 5.6 for the addresses we are going to study, and for all other locations in the Appendix C.

Table 5.6: Indices for via Prada 27, via Pagliolico 48 and via Pradonico 7 case studies

SEISMIC VULNERABILITY INDEX

Category 1	0.45	**Category 1**	0.45	via Pagliolico 48	Via Pradonico 7	Via Baraggia 31
RC		MASONRY		RC	MASONRY	RC
Height	0.275	height	0.2	0.2	0	0
year of construction	0.35	year of construction	0.25	0.7	1	0.7
type of resisting system	0.275	masonry typology	0.25	0	1	0
slab system	0.1	slab system	0.15	0.5	0.5	0
		roofing system	0.15		1	
				0.157	0.326	0.11
Category 2	0.25	**Category 2**	0.25			
RC		MASONRY				
conf plan	0.35	conf plan	0.4	0	0.5	0
conf elev	0.45	conf elev	0.5	0	0	0
infill distribution	0.2	maximum spacing	0.1	0.5	0.5	0
				0.025	0.0625	0
Category 3	0.3					
seismic joints	0.2			0.5	1	1
seismic interventions	0.3			1	1	1
architectural comp.	0.15			0.7	0.7	0.7
plant components	0.1			0.5	0.5	0.5
state of maintenance	0.25			0.5	0.5	0
				0.204	0.234	0.196
				0.387	0.623	0.307

FLOOD VULNERABILITY INDEX

Category 1	0.3	via Pagliolico 48	Via Pradonico 7	Via Baraggia 31
residential type	0.08	0.5	0.75	0.5
year of construction	0.06	0.7	1	0.7
construction material	0.29	0,1	0.4	0.1
external walls cladding	0.12	1	0.8	1
interior walls material	0.1	0.4	0.4	0.2
internal walls cladding	0.17	0.75	0.75	0.75
floor material	0.18	0.2	0.2	0.2
		0.106	0.126	0.1
Category 2	0.45			
number of floors	0.05	0.5	0.5	0.5
basement floor	0.25	1	0	1
ground floor elevation	0.25	1	1	1
floodable floor openings	0.14	0.7	0.7	0.4
presence of check valves	0.12	0.5	1	0.5
floodproofing measures	0.19	0.6	1	0.6
		0.359	0.307	0.34

Category 3	0.25			
electric plant position	0.2	0.2	0.2	0.2
plumbing plant position	0.15	0.5	0.5	0.5
thermal plant position	0.2	1	1	1
thermal plant typology	0.2	1	0.75	0.75
A/C plant position	0.15	0	0	0
emission terminals	0.1	1	0.1	0.1
		0.154	0.119	0.119
		0.619	0.552	0.559

ENERGY EFFICIENCY INDEX

Category 1	0.165	via Pagliolico 48	Via Pradonico 7	Via Baraggia 31
n-er of floors	0.35	0.5	0.5	0.5
S/V	0.25	0.5	0	0
WWR	0.4	0.5	1	1
		0.037	0.066	0.066
Category 2	0.375			
year of construction	0.25	0.6	1	0.8
ext wall stratification	0.18	0.2	0.75	0.2
Stratification of slabs	0.1	0.2	0.75	0.45
external wall cladding	0.05	1	1	1
type of window frame	0.18	0.25	1	0.5
Solar shading	0.15	0.5	1	0
EPC	0.09	0.55	0.95	0.95
		0.16	0.347	0.19
Category 3	0.46			
emission terminals	0.1	0.2	1	1
type of system regulation	0.1	1	0	0
DHW production system	0.15	0.5	0.7	0.5
renewable resources	0.2	0.4	0.4	1
type of heating system	0.05	1	0.7	0.7
A/C system	0.14	0	0	1
type of heat generator	0.2	0.8	1	1
mechanical ventilation	0.06	1	1	1
		0.251	0.214	0.264
		0.448	0.627	0.52

In the Province of Varese, where the three buildings are located, the components of seismic vulnerability and energy efficiency respectively have a weight of about 30% of the total integrated vulnerability, while flood vulnerability has a weight of almost 40%. We will take this information into consideration to evaluate the most convenient and effective interventions to be implemented in order to improve the integrated vulnerability of the houses under investigation.

Suggested interventions for Via Pradonico, 7

Seismic vulnerability is 0.623; flood vulnerability is 0.552 and energy efficiency is 0.627. In this case, all the vulnerabilities are relatively high, so we could implement actions involving several indices, favouring the reduction of flooding vulnerability and seismic vulnerability.

We certainly recommend the application of check-valves, which have a great contribution in reducing flood vulnerability and are an inexpensive intervention. Furthermore, as floodproofing measures are absent, we recommend the application of temporary barriers (dryproofing). With these two interventions, the weight of category 2 of flood vulnerability index becomes 0.219 and the flood vulnerability index itself becomes 0.464.

Analysing the seismic vulnerability index, we realise that two of the factors that most penalise the final result are the type of masonry and the absence of anti-seismic interventions. We therefore propose upgrading with a fiber-glass reinforced plaster to increase safety for both factors. In this way, category 1 takes on a value of 0.214. Category 3, on the other hand, drops to 0.144. With this intervention, the seismic vulnerability becomes 0.42.

It is considered necessary to also intervene to improve energy efficiency, and in particular on category 2, which is the one that weighs the most. This is why we propose to include movable solar shading, so as to reduce the weight of category 2 to 0.291. By doing so, the energy efficiency index becomes 0.571.

In this way, the integrated vulnerability of the house at via Pradonico 7 becomes:

$$0.42 \times 30.35\ \% + 0.464 \times 39.26\ \% + 0.571 \times 30.39\ \% \ = \ 0.483\ \%$$

which results reducing the integrated vulnerability of 11.3 %.

Suggested interventions for via Pagliolico 48.

Seismic vulnerability is 0,387; flood vulnerability is 0,619 and energy efficiency is 0,448. Therefore, since the worst index also corresponds in this case with the most weighted vulnerability (flood), we consider it appropriate to work on this aspect in order to have the greatest benefits on integrated vulnerability.

The three categories of the flood vulnerability index share the weight as follows: Category 1 0.106; Category 2 0.359; Category 3 0.154.
It is therefore clear that the category that most penalises vulnerability is Category 2, followed by Category 3.

In category 2, the factors that most penalise vulnerability are the presence of basement and ground flood elevation, but unfortunately these are elements on which we cannot, or it is not economically viable to intervene. Instead, we could intervene, inserting wetproofing measures, eliminating manholes and applying check valves. These interventions have no effect on the other vulnerability indices. With these simple measures, category 2 drops from a weight of 0.359 to a weight of 0.236.

In category 3, the type of emission terminals could be changed, but by reducing the flood vulnerability, energy efficiency would be penalised, so we will avoid this expedient, also because the intervention to remove the radiant floor panels is very costly.

Considering the energy efficiency index, the category that most penalise the vulnerability is category 3 (0.251). To improve the energy efficiency, we can opt for climate regulation instead of thermostat, and we can install a mechanical ventilation system. With these actions, category 3 of energy efficiency index drops to 0.177, and the overall value of the energy efficiency index becomes 0.374.

In this way, the integrated vulnerability of the house at via Pagliolico 48 becomes:

$$0.387 \times 30.35\% + 0.496 \times 39.26\% + 0.374 \times 30.39\% \;=\; 0.426\ \%$$

which results in reducing the integrated vulnerability of 7%.

Interventi suggeriti per via Baraggia 31

Seismic vulnerability is 0,307; flood vulnerability is 0,559 and energy efficiency is 0,52. The index that is the most penalising is the flood vulnerability index, which also corresponds to the greatest losses, followed by the energy efficiency index. Therefore, we will focus on improving flood safety and energy efficiency

The factors that weight the most, also with reference to the weight of the categories, are related to the factors in category 2, so we will start by analysing how to improve this category.

We do not know if check valves are present, but we can make the hypothesis of applying them. In addition, there are dryproofing measures, which can be combined with wetproofing measures. In this way, category 2 of the flood vulnerability index takes on a value of 0.262.
With these measures, the flood vulnerability index assumes the value of 0.481.

Concerning the energy efficiency index, the most penalising category is the third (0.264). Considering the introduction of renewable resources and of a mechanical ventilation system, the value of this category becomes 0.144 and the energy efficiency index takes the value 0.4.

Thus, the integrated vulnerability of the dwelling at via Baraggia 31 becomes:

$$0.307 \times 30.35\ \% + 0.481 \times 39.26\ \% + 0.4 \times 30.39\ \% = \ 0.403\ \%$$

which results in reducing the integrated vulnerability of 6.8 %.

The suggested interventions are selected following the principle of mostly reducing the integrated vulnerability with the smallest number of interventions. In the case of actual application of these interventions, it is necessary to perform a cost-benefit analysis on the specific building, considering the EALs at the building scale and evaluating the costs for the interventions and the possibility for them to be put into practice.

5.3.2. Use of the methodology to verify the goodness of an intervention. Bergamo case study.

The building under investigation is located in the municipality of Bergamo, more precisely in the 'Villaggio degli Sposi' (The Spouses' Village). It is a building owned by the Aler company, intended for fragile social categories.

The purpose of this analysis is to estimate the improvement in the general conditions of vulnerability of the building, given the same local conditions (same loss for pre and post). It is important to emphasise that many of the changes that will be made are not applicable to the case of existing buildings that are being refurbished (such as the year of construction or the construction material), so we expect a greater improvement in integrated vulnerability in this case, compared to the cases analysed previously.

<u>Bergamo Pre</u>

The building, dated back to the 1960s, has an L-shaped plan configuration (80x60 m) and has 4 floors (+ basement destined for cellars). The precarious safety conditions, the absence of thermal insulation, the need to overcome the limits imposed by the architectural barriers and the general inadequate condition of the technological components (Figure 5.1) required a timely redevelopment, which will be carried out by demolishing the building and rebuilding it from scratch.

Figure 5.1: Detail of the severe degradation of the building

Bergamo Post

The new building will be a rectangular 4 storey structure, with high structural regularity and compactness. The construction material will be XLAM engineered timber which has extremely good performances under seismic actions, but is not recommended for floodable area. Nevertheless, the first floor is raised (1.1 m) and the basement is made of reinforced concrete, so it is considered that there is still some level of protection from water.

In our procedure, we did not have an index for the timber structures, however due to the good performances of this material (strong box behaviour so no issues with pushing roofs and good connection between orthogonal walls), it was possible to assimilate it to the case of reinforced concrete.

The walkable flat roof reduces the horizontal actions and reduce the risk due to the falling of tiles.

The presence of insulation of the external walls is an advantage on the behalf of energy efficiency, but increases the flood vulnerability, and so does the absence of check-valves, the absence of floodproofing measures and the opening toward the basement. The position of plants is generally higher than the expected water height, exception made for the electric plant, located in the basement.

For energy efficiency, the building is designed to be in class A2-A3. The district heating is used both for heating and for the air conditioning, and the thermal plant in Bergamo is powered by gas. Balconies provide o fixed solar shading, and the windows ad double glazed in PVC. The emission terminals are floor panel. This solution improved the energy performance, but might be damaged in the eventuality of a flood. We recall that the first floor is raised, so there is a lower probability that the water height reaches 1.1 m (the reference flood in Bergamo had a height of 85 cm).

Table 5.5 shows the assessment of the vulnerability indices for the existing building (Bergamo Pre), quantified on the basis of the data collected during the inspection, and for the building to be constructed (Bergamo Post), quantified according to the new design projects.

As we can clearly see, there is an important improvement of the integrated vulnerability of the structure, meaning that the intervention is valuable. Comparing the indices, we can see how the presence of seismic norms and energy efficiency requirements has an impact on the final design. In fact, the major improvement is obtained for the seismic vulnerability index, from 0.695 to 0.089, and for the energy efficiency index, from 0.686 to 0.306. The aspect of flood vulnerability was a little neglected, and this is reflected by the fact that we have almost a null improvement in flood vulnerability index, from 0.599 to 0.579. This aspect is the most important to analyse.

At the state of the art, the absence of regulations regarding the risk of floods for buildings makes it possible to build a new structure which is as vulnerable as a structure which has to be demolished built in the 1960s.

Overall, we can state that the project is satisfactory, since there is a reduction of around 35 % of the integrated vulnerability. Nevertheless, we suggest a revision of the project, inserting some measures to protect the structure from the action of water, and eventually a more in-depth analysis to have an estimate of the water height that are expected at the location, in order to verify that the timber structure, placed at 1.1m above the ground level, is safe.

6 Conclusions

To conclude, we would like to address the limitations, advantages and future perspectives of the methodology we have developed.

The limitations of the methodology mainly concern two aspects: the first is linked to the possibility of collecting the data necessary for compiling the indices and evaluating the EALs; the second aspect is related to the fact that the vulnerability indices, with the weights and scores we have proposed, is only applicable to residential buildings in Italy, built in masonry or RC.

The difficulty in collecting all the data needed to compile the indices is mainly due to the lack of documentation available to homeowners and, sometimes, to the impossibility of gathering information related to structural aspects of the building. In fact, information on the original projects of the dwellings, on the plans of the installations, on the subsequent modifications made to the building over the years, etc... is often lost (since this is a methodology for a cursory assessment of the vulnerability of buildings, it is not considered coherent to carry out such an in-depth investigation as to imply demolition or wall inspection to characterise the type of construction, position of the installations, etc. The information will either be obtained from documentation, plans, or the testimony of the tenants or will be estimated; in the worst case we will apply a mean score to the factor). This implies that in order to obtain the information we need, factor values must be approximated and/or estimated using more general notions, or that in-depth investigations, which are time-consuming and costly, must be carried out to obtain the necessary documentation from the technical offices of the municipalities.

The second aspect of data collection concerns the data needed to assess EALs. In the case of seismic risk, in Italy today we are lucky to have a legislation that provides the PAM (Mean Annual Loss) according to the vulnerability of the building and the seismic zone, so we can apply the procedure described in 4.2.1 in all locations throughout the Italian national territory, and if appropriate, even with a higher level of precision.

The same applies to energy EAL. In fact, we have considered the data for the standard $EP_{gl,nren,ref,standard}$ of the provinces of Bergamo and Varese for residential buildings, but by collecting data for other provinces and/or for other categories of buildings (industrial, offices, commercial, etc.) it is possible to easily adapt the methodology to a large part of the built heritage. On the other hand, as far as the assessment of flood EAL is concerned, the situation is more complicated. In our case, we were able to take advantage of the damage curves and the hazard scenarios provided by the Po river district authority, but in many cases, there is a total lack of information regarding damage curves or models estimating water heights corresponding to certain probabilities of occurrence. In these cases, alternative methods for loss assessment will have to be found.

However, the fact remains that this study, like many others, has highlighted how problematic, for research and safety purposes, is the lack of a unified mapping of the national territory according to the water heights predicted for different probabilities of occurrence (or return time) of the flood event.

The second limitation that we can highlight is the fact that the integrated vulnerability index, as we have defined it, can only be applied to the provinces of Bergamo and Varese, and that in any case the vulnerability indices (due to the weights assigned to the factors and the factor scores) are only applicable to residential buildings in masonry or reinforced concrete in Italy.

However, while it is true that the integrated vulnerability index with weights and scores as we propose it here is applicable in a few very specific cases, it is also true that the very nature of the methodology makes it extremely adaptable. In fact, we would say that adaptability and flexibility are the greatest strengths of the proposed methodology.
Indeed, one can readjust the integrated vulnerability index by considering different types of risk, or different building types. Or even easier the methodology can be readapted to other locations.

To readapt the integrated vulnerability index to different risk typologies, it is suggested to start from the desk research. For the new type of risk, the factors that contribute to generating the vulnerability index must be defined, depending on the type of buildings considered. The values and scores associated with the factors must be defined, and the weight of the factors must then be chosen, using the Delphi methodology or other investigation methods that, on a case-by-case basis, are considered more suitable. Finally, the combination coefficients should be recalibrated to obtain the new integrated vulnerability index.

For example, if one is interested in the integrated vulnerability to seismic, flood and fire risk, for residential buildings in Italy, one could simply assemble the fire risk vulnerability index, substitute it to the energy efficiency index and then recalibrate the combination coefficients according to the EALs at the location under consideration.

If, on the other hand, one wants to apply our same integrated vulnerability index in another country, we suggest a preliminary investigation to assess the weight of the factors, as building traditions and local conditions could influence the importance of certain factors or require to consider other and/or different factors. This also emerged in our research, as we saw how Italian and international experts belonging to the same panel gave greater importance to different factors.

Another advantage of this methodology that we would like to emphasise is the speed of application. In fact, if the rapidity of application often makes data collection a little more approximate, at the same time it allows the methodology to be applicable on a large scale, to assess vulnerability at the municipal and/or provincial level. We can estimate that, net of the creation of the integrated vulnerability index, between the on-site survey of the building under investigation (estimated 1,5h) and the compilation of the indices (estimated 30 min), approximately 2 hours are needed to assess the integrated vulnerability of a residential building.
This means that, for example, to assess the integrated vulnerability of the totality of residential buildings in the municipality of Bergamo can be estimated by a research group of 20 members in 12 months (21 working days of 8 hours):

- 121200 inhabitants in 2017, estimated 20200 dwellings (6 inhabitants x residential building); [13]
- we need 5050 working days.

However, we must consider that this estimate considers much more time than the real, since the majority of buildings are very similar and so their evaluation is faster.

In conclusion, we would like to emphasise one last time the importance of risk assessment and risk management, and how a careful study and proper risk mitigation, which considers the interactions between different risks and the combined effects they have on buildings, can bring significant benefits to both building owners and the state, and these benefits are not only measured in economic terms, but also and above all in terms of people's quality of life.

We hope that this research will once again draw attention to the topic of risk, and that it will promote further research on the topic of integrated vulnerability. We also hope that this methodology is only the starting point and that there will be subsequent studies on the subject of integrated vulnerability and risk mitigation, in a context that takes into account the interaction between the risks present and preponderant in a given place, so that we can choose wisely which actions to take, in order to achieve the best result in terms of safety, with the least amount of money, and being as sustainable as possible.

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INTRODUCTION

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A Appendix A

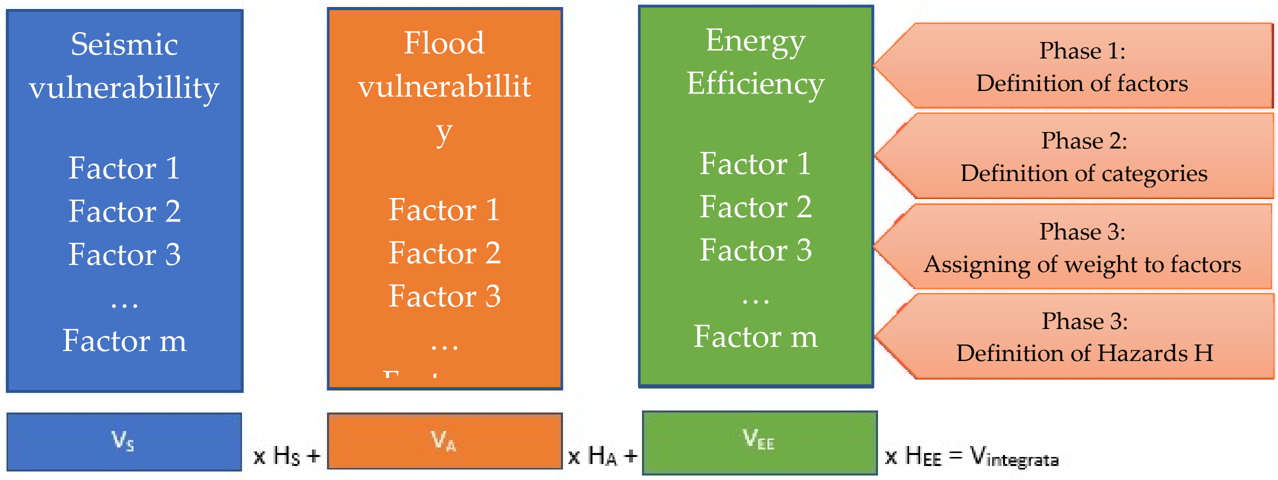
The following questionnaire is positioned as the initial phase of an integrated vulnerability study related to flood risk, seismic risk, and building energy efficiency. The purpose is to identify a single index that can indicate what the overall vulnerability of a building is, for the purpose of more effective management of interventions. The study aims to provide a tool that can be valid for:

- residential buildings of any type;
- buildings located in any area of the national territory;
- buildings located in areas where the site hazard may be due in varying proportions to seismic and flood risks and where energy efficiency interventions need to be implemented.

For the purpose of this assessment, individual vulnerabilities will first be assessed. Only after obtaining a vulnerability value for each "risk" can the information obtained be aggregated, depending on the hazard and climatic characteristics of the site where the building is located.

At the preliminary stage of the study, based on the relevant literature, the main factors affecting individual vulnerabilities were identified. With this questionnaire, we ask you, as experts, to give a weight to the individual vulnerability factors identified that is representative of the factor's importance in defining the total vulnerability of the building.

For clarity, the diagram below summarizes the steps identified for the integrated vulnerability assessment.



To facilitate the weighing operation, the factors have been expertly grouped into categories. We ask you, first, to associate a weight with each category (Pi), such that the sum of the

category weights is unity.
Next, we ask you to associate a weight (pi) with the factors contained in each category, according to the criterion that within each category the sum of the weights should equal unity. In this way, the weight of the individual factor will be given by the product of the weight of the category and the weight of the factor within that category.
Finally, the vulnerability of the building will be given by the following formula:

$$\sum_{i=1}^{n} P_i \left(\sum_{j=1}^{m} p_j v_k \right)$$

Where:

n = number of categories
m = number of factors within the individual category
v_k= value assumed by factor j in category i (appropriately reclassified on a scale from 1 to 10).

Schematizing (example for one category):

$$category\ i\ (weight\ P_i) \begin{cases} Factor\ 1\ (p_1) \begin{pmatrix} value\ 1\ (v_{11}) \\ value\ 2\ (v_{12}) \\ \dots \\ value\ k\ (v_{1k}) \end{pmatrix} \\ Factor\ 2 (p_2) \begin{pmatrix} value\ 1\ (v_{21}) \\ value\ 2\ (v_{22}) \\ \dots \\ value\ k\ (v_{2k}) \end{pmatrix} \\ \dots \\ Factor\ m\ (p_m) \begin{pmatrix} value\ 1\ (v_{m1}) \\ value\ 2\ (v_{m2}) \\ \dots \\ value\ k\ (v_{mk}) \end{pmatrix} \end{cases}$$

In what follows, you will first be provided with a description of the individual categories and the related factors identified for your risk. Then, you will be provided with an outline where you can provide your judgment and any comments and/or suggestions

The following steps are recommended for completing the questionnaire:
1. First read the entire questionnaire, without thinking about assigning any values. This step serves to gain an overview of the problem in all its components.
2. Carefully reread the definitions of categories and factors.
3. Only then proceed to assign value to the individual categories, always remembering that the sum of the weights must equal 1.
4. Then it will be possible to move on to defining the weights of the individual indices. At this stage you will need to focus only on the weight that the individual indices have within the category, and assign these weights so that the sum, within each category, is equal to 1.

Note: in the COMMENTS section you should enter REASONS FOR CHOOSING A WEIGHT VALUE, whereas, in the SUGGESTIONS section you should enter EVENTUAL SUGGESTIONS of any kind, including changes that the expert deems necessary (e.g., on other factors to be considered, factors to be neglected, how to define the factor, etc.).

IT IS IMPORTANT THAT ANY CHOICES OR COMMENTS BE ARGUED, SO THAT THIS INFORMATION CAN BE PROVIDED TO THE POOL OF EXPERTS INVOLVED, WHO MAY MODIFY OR CONFIRM THEIR INITIAL JUDGMENT, AT A SECOND STAGE OF THE INVESTIGATION.

SEISMIC VULNERABILITY INDEX

Category 1: Structural characteristics of the building.

This category contains factors related to the structural characteristics of the building. These factors affect the way the structure sways, its stiffness or flexibility, the possible presence of rigid diaphragms at the floor level etc.
Thus, the category "structural characteristics of the building" comprehensively represents all the vibration, design capacity and current capacity characteristics of the structure.

Weight category 1 (P1)	
Comments	
Suggestions	

Category 2: Structural Regularity.

This category contains all factors related to the presence or absence of structural regularity, in terms of planform configuration and elevation configuration. Note that regularity and symmetry are to be understood in terms of both mass distribution and stiffness distribution.

Weight category 2 (P2)	
Comments	
Suggestions	

Category 3: Interventions that occurred during the life of the structure.

The last category concerns interventions that have occurred during the life of the structure. In fact, if part of the characteristics of a building can be deduced from the original plans, it is not negligible what happened to the structure during its operation.
This issue is of particular relevance in Italy, where about 70 percent of the built heritage is more than 50 years old.
With this category of factors, we aim to assess interventions that occurred after construction and thus made changes, whether ameliorative or not, to the building's capacity.

Weight category 3 (P3)	
Comments	
Suggestions	

Category 1: Structural characteristics of the building.

- *Height of the building*
  Building height refers to the portion of the building above street level. It is an indicator for the vibration period of the structure.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Year of construction*
  The year of construction is a factor that was considered because it is representative of both the state of wear and tear on the building and the regulatory framework in place at the time of design and construction.

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Type of resisting system*
  By type of resisting system is meant whether the structure is frame, resisting wall, mixed frame-wall structure, pendulum etc.

Weight factor 3 (p3)	
Comments	
Suggestions	

- *Foundations*
  There are two main types of foundations, surface (slab) and deep (pile foundation) foundations.

Weight factor 4 (p4)	
Comments	
Suggestions	

- *Roofing system*
  Roofs are classified according to their action on the structure. Thus, one finds pushing, partially pushing and non-pushing roofs. In addition, another classification criterion is according to the weight of the roofing element.
  For this study we are going to classify roofs as:
  - heavy pushing or partially pushing;
  - light pushing or partially pushing;
  - light non-pushing.

Weight factor 5 (p5)	
Comments	
Suggestions	

- Slab system
  The type of slab system can be classified on the basis of the horizontal structural system, which can be flexible, such as timber slabs, or rigid, such as hollow core slabs.

Weight factor 6 (p6)	
Comments	
Suggestions	

Category 2: Structural Regularity.

- *Planimetric configuration*
  By plan configuration we mean whether the building is regular in plan or not.
  To this end, the distribution of stiffnesses must be approximately equal in the two orthogonal directions and the plan form is compact, i.e. there are no projecting elements or localised concavities.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Configuration in elevation*
  The configuration in elevation, similarly to the configuration in plan, is an indicator of the regularity in elevation of the structure.
  In order to be considered regular in elevation, a building must fulfil the following conditions
  - no abrupt changes in the size of the storeys;
  - the stiffness of the columns must not be reduced by more than 30% and must not increase by more than 10%;
  - no interruption or change in the resistance systems in elevation.

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Maximum masonry spacing*
  The masonry distance factor indicates whether the distance between walls of masonry buildings is less than 5m.
  In the case of non-masonry buildings, this factor defines the maximum ceiling span.

Weight factor 3 (p3)	
Comments	
Suggestions	

Category 3: Interventions that occurred during the life of the structure.

- *Presence of seismic joints*
  Joints are elements designed to interrupt the continuity of the structure in order to prevent seismic damage. Earthquake-resistant joints allow sufficient displacement of the oscillating parts without inducing damage to adjacent portions.
  These elements can be inserted at a later stage of construction. Dampers, which are devices designed to dissipate earthquake energy (viscous dampers, hysteretic dampers...), are also considered in this factor.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Seismic interventions*
  Earthquake interventions are defined as actions to reduce the overall vulnerability of the building. The classification of these interventions depends on the value of the safety index (ζ=(PGA capacity)/(PGA Design)) that they manage to achieve.
  Earthquake interventions are classified into:
  - retrofitting (ζ≥1);
  - improvement (0.1 <ζ<1);
  -local interventions (ζ>0.1).

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Architectural components*
  By architectural components we mean, belfries, chimneys, balconies, etc., and more generally all those architectural elements that are not structural but have a significant mass, which can therefore be subject to earthquake-induced inertia forces.

Weight factor 3 (p3)	
Comments	
Suggestions	

- *Plant components*

  By this we mean the presence of plant components, such as pipes, ventilation ducts, heating systems, etc.

  We will classify the plant components according to their position within the structure, i.e:
  - installations whose accommodation was defined at the design stage;
  - systems added after construction, but positioned so as not to reduce the load-bearing capacity of the building;
  - installations added after construction, but positioned in such a way as to reduce the load-bearing capacity of the building;

Weight factor 4 (p4)	
Comments	
Suggestions	

- *State of maintenance*

  The state of maintenance is an index relating to the condition (state of affairs) of the structure.

  The state of repair refers to the condition of the masonry, floors, windows, etc.

Weight factor 5 (p5)	
Comments	
Suggestions	

FLOOD VULNERABILITY INDEX

Category 1: Structural type and construction materials

This category includes all factors related to the structural characteristics (year of construction, construction type and material) and cladding materials of the building. This category then goes to assess what the building's propensity for physical damage is.

Weight category 1 (P1)	
Comments	
Suggestions	

Category 2: Propensity to flooding.

This category includes all those features that may or may not favor the entry of water into the building. This may depend both on the presence of basement floors and the height of the entrance relative to the floodable elevation, as well as on how many openings are present in the lower floors.

Weight category 2 (P2)	
Comments	
Suggestions	

Category 3: Location of facilities

The following category goes to define what the location (and type) of the plumbing, heating, and air conditioning system is.

Weight category 3 (P3)	
Comments	
Suggestions	

Category 1: Structural type and construction materials

- *Year of construction*
  The year of construction factor refers to the year of completion.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Residential type*
  Residential types are distinguished on the basis of the way in which the individual units are grouped together, distinguishing between: courtyard house, cottage, condominium, townhouse, etc...

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Construction material*
  The construction material refers to the material of the load-bearing structure, which can be concrete, masonry, steel, wood, etc...

Weight factor 3 (p3)	
Comments	
Suggestions	

- *Exterior wall cladding*
  There are different cladding materials for external walls, such as uninsulated plaster, exposed brick or stone facade, insulated plaster (coat) gress, etc...

Weight factor 4 (p4)	
Comments	
Suggestions	

- *Interior wall material*
  The material of internal walls refers to the material of non-load-bearing partition structures, which can be concrete, solid masonry, non-load-bearing masonry, wood, plasterboard, etc…

Weight factor 5 (p5)	
Comments	
Suggestions	

- *Interior wall cladding*
  There are different cladding materials for external walls, such as wood, plaster, waterproof paint, wallpaper, paper, ceramics, etc...

Weight factor 6 (p6)	
Comments	
Suggestions	

- *Floor materials*
  There are different materials that can make up the floorings of a building, some of which are presented below: parquet, carpet, ceramic/gress, PVC, stone, etc...

Weight factor 7 (p7)	
Comments	
Suggestions	

Category 2: Propensity to flooding.

- *Number of floors*
  This means the number of floors above ground.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Presence of basement floors*
  Basement floors will be considered as all floors that are not raised (this index is the "complementary" to the previous one). Examples are floors used for cellars and garages.

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Ground floor elevation hg*
  The ground floor elevation refers to the difference in height between the street level and the entrance floor.

Weight factor 3 (p3)	
Comments	
Suggestions	

- *Floodable floor openings*
  This is defined as the area of doors, windows or any other type of opening present on floors that are below the maximum flood height. This is defined as the maximum height, in relation to sea level, that water can reach following a flood event. These heights are defined in the hazard maps of the location.

Weight factor 4 (p4)	
Comments	
Suggestions	

- *Presence of check valves*
  This factor indicates the presence or absence of non-return valves serving the hydraulic system.

Weight factor 5 (p5)	
Comments	
Suggestions	

- *Floodproofing measures*
  This index is intended to consider all floodproofing measures, both active and passive. Floodproofing measures can be both designed together with the structure, but can also be added at a later stage.
  Furthermore, floodproofing measures can be either permanent or mobile.

Weight factor 6 (p6)	
Comments	
Suggestions	

Category 3: Location of facilities

- *Electrical system position*
  With this factor, it is required to define the elevation relative to the floor of the control cabinet, so that it can be understood whether it is above or below the floodproof level.

Weight factor 1 (p1)	
Comments	
Suggestions	

- *Plumbing system position*
  This factor is used to define the floor level of the plumbing system (boiler, etc.) so that it can be understood whether it is above or below the flood level.

Weight factor 2 (p2)	
Comments	
Suggestions	

- *Thermal system position*
  With this factor, we are asked to define the height above the floor of the heating system (boiler), so that we can understand whether it is above or below the floodable level.

Weight factor 3 (p3)	
Comments	
Suggestions	

- *Heating system type*
  The thermal water heating system, whether for hygienic or heating purposes, uses boilers. The type of system (traditional boilers, gas boilers, condensing boilers, etc.) is also considered here.

Weight factor 4 (p4)	
Comments	
Suggestions	

- *Air conditioning system location*
  With this factor, you are asked to define the height in relation to the floor of the air-conditioning system, so that you can work out whether it is above or below the flood level.

Weight factor 5 (p5)	
Comments	
Suggestions	

- Emission terminals
  By emission terminals we mean the type of terminal used to emit heat into the room. Some types of terminals are: radiators, fancoils, radiant panels (ceiling, wall, floor), hot/cold air vents, convectors, etc...

Weight factor 6 (p6)	
Comments	
Suggestions	

ENERGETIC VULNERABILITY INDEX

Category 1: Typological characteristics

This category encompasses the factors characterising the structure of the building in terms of area/volume ratio, number of floors and windows to walls ratio.

Weight of category 1 (P1)	
Comments	
Suggestions	

Category 2: Performance characteristics

This category includes the building's construction characteristics that have an impact on its energy performance, such as wall and floor coverings, types of fixtures, sun screens, etc.

Weight of category 2 (P2)	
Comments	
Suggestions	

Category 3: Plant engineering

The following category considers all aspects of plant engineering, relating to the types of installations and emission terminals, both domestic water heating and air conditioning systems, as well as sources from renewable sources, etc.

Weight of category 3 (P3)	
Comments	
Suggestions	

Category 1: Typological characteristics

- *Surface-to-Volume Ratio*
  This factor basically indicates how compact the building is (and therefore inherently more energy efficient)

Weight of factor 1 (p1)	
Comments	
Suggestions	

- *Number of floors/Building height [m]*
  Means the number of floors above ground, or equivalently the height of the building [m].

Weight of factor 2 (p2)	
Comments	
Suggestions	

- *Windows to wall ratio*
  The window to wall ratio is an index that identifies air-to-light ratios. Values can range from about 15% to 80-90% for fully glazed buildings.

Weight of factor 3 (p3)	
Comments	
Suggestions	

Category 2: Performance characteristics

- *Year of construction*
  Refers to the year the final project was approved. The reference values are: pre 1973, 1973-91, 91-2005, 2005-15, post 2015.

Weight of factor 1 (p1)	
Comments	
Suggestions	

- *External wall stratification*
  This factor defines how the stratification of walls that have one side facing outwards is composed (massive/light insulated/uninsulated structures).

Weight of factor 3 (p3)	
Comments	
Suggestions	

- *Stratification of slabs towards the outside or unheated rooms*

  This factor defines how the layering of slabs corresponding to external areas or unheated rooms of the building (insulated/uninsulated massive/lightweight structures) is composed.

Weight of factor 4 (p4)	
Comments	
Suggestions	

- *External wall cladding*

  This refers to the colour (light or dark) of the external cladding.

Weight of factor 5 (p5)	
Comments	
Suggestions	

- *Type of window frames*

  This factor defines the technical characteristics of window frames, both glazing and supports (frame, single/double glazing, with or without thermal break).

Weight of factor 6 (p6)	
Comments	
Suggestions	

- *Solar shading*

  By solar shading we mean here the presence or absence of fixed or movable screens that protect the interior of the house from the direct action of the sun's rays.

Weight of factor 7 (p7)	
Comments	
Suggestions	

- Energy Performance Certificate

  The energy performance certificate summarises the quality level of the building, both in terms of energy and economic value.

Weight of factor 8 (p8)	
Comments	
Suggestions	

Category 3: Installations

- *Type of emission terminals*
  By emission terminals we mean the type of terminal used to emit heat into the environment. Some types of terminals are: radiators, fancoils, radiant surfaces (ceiling, wall, floor) ...

Weight of factor 1 (p1)	
Comments	
Suggestions	

- *Type of system regulation*
  The type of system regulation refers to whether the system is controlled by a thermostat, on-off system or via climate regulation.

Weight of factor 2 (p2)	
Comments	
Suggestions	

- *Type of DHW production system*
  Mainly the modes of Domestic Hot Water production are electric or fossil-fuel fired boiler, solar thermal system and heat pump.

Weight of factor 3 (p3)	
Comments	
Suggestions	

- *Presence of installations powered by renewable sources*
  This factor defines whether there are installations powered by renewable sources, and if so, how much power is generated per housing unit.

Weight of factor 4 (p4)	
Comments	
Suggestions	

- *Type of heating system*
  The heating system can be of two main types, stand-alone or centralised, with or without thermoregulation/containment.

Weight of factor 5 (p5)	
Comments	
Suggestions	

- *Summer air-conditioning system*
  This factor indicates, if there is one, what type of summer air-conditioning system, e.g. split for each flat, centralised cooling unit...

Weight of factor 6 (p6)	
Comments	
Suggestions	

- *Type of heat generator*
  The heat generator can take the form of boilers (traditional fuel-fired, fuel-fired condensing), hybrid or district heating systems, heat pumps or biomass systems.

Weight of factor 7 (p7)	
Comments	
Suggestions	

- *Presence of controlled mechanical ventilation system*
  This factor is used to indicate the presence or absence of controlled mechanical ventilation systems in none, some or all of the units in the building.

Weight of factor 8 (p8)	
Comments	
Suggestions	

B Appendix B

EXAMPLE OF QUESTIONNAIRE ON FLOOD RISK – PHASE 2

	weight proposed	your proposal	JUSIFICATION OF THE PROPOSED WEIGHT
CATEGORY 1	0,3		We suppose that, even though each category is important, this should have a lower weight with respect to category 2
year	0,07		the year of construction could be used as a proxy for the construction type when details on the type of structure is unknown. Year of construction can also be a proxy for "state or aging" of the material. It could give an idea of the standards implemented in the structural design of the building, that in the case of extreme events can influence the occurrence of structural damages such as collapse.
residential typology	0,1		This factor has a lower impact in general, it's more significant when we distinguish between apartment buildings and detached/semi-detached buildings
construction material	0,14		For the material characteristics used for the cladding, external walls have generally a lower vulnerability with respect to the internal walls and floors
external wall cladding	0,14		
internal wall material	0,12		For the most frequent flood intensity in Italy, we think that the claddings of walls and floors have an importance influence on vulnerability
internal wall cladding	0,21		
floor material	0,22		Some typologies of floor's material result particularly vulnerable with respect to floods (moquette, wooden floor). The use of waterproof materials, easy to wash guarantee a lower damage.
CATEGORY 2	0,45		
number of floors	0,05		Very important factor, especially for low height of floods. Even at very low water levels the presence of basement can increase damage highly.
basement floor	0,25		
ground floor elevation	0,25		This factor can make substantial difference to the entry of water, but only secondarily in comparison to other factors of this category (such as height).
floodable floor openings	0,14		
presence of check valves	0,12		Although such measures can have a large effect, a single indicator for varied measures will have a lower (averaged) weight.
floodproofing measures	0,19		
CATEGORY 3	0,25		HOW TO FILL IN THIS QUESTIONNAIRE
electrical system position	0,2		In the first phase, we asked you as expert in the field of flood risk to give a weight to the vulnerability factors. Gathering all the answers, it was possible to obtain a mean weight that could satisfy the majority of experts. In this second phase we ask you to think again about the weight of only those factors for which your answer was significantly different from the mean answer, and to this end we provide you with the comment of other experts So we will propose a weight, and in the box "your proposal" you can write: the same weight if you agree with us; another weight if you do not agree; For a good outcome of the procedure, we ask you to deeply consider the other experts opinion when evaluating the new weight to be assigned REMEMBER TO ASSIGN A NEW WEIGHT ONLY TO THE FACTORS HIGHLIGHTED
plumbing system position	0,15		
thermal system position	0,2		
heating system type	0,2		
A/C system position	0,15		
emission terminals	0,1		

QUESTIONNAIRE OF SEISMIC RISK – PHASE 2

Category 1				0,45	
RC	weight proposed	your proposal	MASONRY	weight proposed	your proposal
height	0,15		height		
year of construction	0,25		year of construction	0,25	
type of resisting system			masonry typology		
foundations	0,05		foundations	0,05	
slab system			roofing system	0,15	
			slab system		
Category 2				0,25	
RC	weight proposed	your proposal	MASONRY	weight proposed	your proposal
conf plan			conf plan	0,4	
conf elevation			conf elevation	0,5	
infill distribution			maximum spacing	0,1	
Category 3				0,3	
	weight proposed	your proposal			
seismic joints	0,19				
seismic interventions	0,3				
architectural components	0,15				
plant components	0,1				
state of maintenance	0,26				

HOW TO FILL IN THIS QUESTIONNAIRE

In the first phase, we asked to you as experts to give us your opinion regarding the weights and the choice of factors to evaluate the seismic vulnerability of a residential building. What emerged was that there is the need for different factors when we deal with masonry or reinforced concrete structures. We followed this advice of yours. At this stage we ask you to fill in again this updated questionnaire, following always the criteria that the sum of categories is equal to 1 and inside each category the sum of factor's weight is equal to 1.

Gathering all the informations obtained from the previous questionnaire, we were able to suggest some factor's weights. So, for some factors, we will propose a weight, and in the box "your proposal" you can write: the same weight if you agree with us; another weight if you do not agree;

We suggest to first assign the weight to the factors which have a proposed weight, and then filling the rest

CHANGES WITH RESPECT TO PHASE 1

According to the results of the first questionnaires, we decided that it was necessary to divide the first and second categories with respect to the construction material. Hence, in this second questionnaire, we ask you to weight the factors considering the two separate cases of reinforced concrete and masonry.

Category 1

for what concerns masonry, in the first category we have substituted the factor "type of resisting system" with "masonry typology*" which results to be more meaningful.

for what concerns reinforced concrete structures, we have eliminated the factor "roofing system" which was significant only in the case of masonry structures.

Category 2

for what concerns masonry, the category remained the same

for what concerns reinforced concrete, we have substituted the factor "maximum masonry spacing" with the factor "infill distribution**"

Category 3 remained the same for both structural typologies

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*masonry typology is a factor which considers the goodness of masonry. Some examples of masonry typologies are: squared stone masonry, irregular stone masonry, mixed masonry etc…

**infills are non-structural elements that, if not properly placed, can cause damage to the structure. Examples of infill distributions are: irregular distribution in plan or elevation, infills causing short columns etc…

C Appendix C

SEISMIC VULNERABILITY INDEX

	Weight		Weight	Cugliate-Fabiasco			Cunardo			Marchirolo		Bergamo	
				via Pagliolico 48	Via Torino 61D	Via S.Pietro 35B	Via Verdi 11	Via Pradonico 7	Via Prada 27	Via Baraggia 31	Via Statale 36	Bergamo Pre	Bergamo Post
Category 1	0,45	**Category 1**	0,45										
RC		MASONRY		RC	RC	RC	RC	MASONRY	MASONRY	RC	RC	MASONRY	TIMBER-RC
height	0,275	height	0,2	0,2	0,2	0	0,2	0	0,2	0	0,2	0,2	0,2
year of construction	0,35	year of construction	0,25	0,7	0,7	0,7	0,7	1	0,7	0,7	0,7	1	0,1
type of resisting system	0,275	masonry typology	0,25	0	0	0	0	1	1	0	0	1	0
slab system	0,1	slab system	0,15	0,5	0,5	0	0	0,5	0,5	0	0	0,5	0
		roofing system	0,15					1	0,5			0,5	
				0,1575	0,1575	0,11025	0,135	0,32625	0,27675	0,11025	0,135	0,3105	0,0405
Category 2	0,25	**Category 2**	0,25										
RC		MASONRY											
conf plan	0,35	conf plan	0,4	0	0	0	0	0,5	0,5	0	0	1	0
conf elev	0,45	conf elev	0,5	0	0	0	0	0	0,5	0	0	0	0
infill distribution	0,2	maximum spacing	0,1	0,5	0,8	0	0,5	0,5	0,5	0	0	0,5	0
				0,025	0,04	0	0,025	0,0625	0,125	0	0	0,1125	0
Category 3	0,3	materials											
seismic joints	0,2			0,5	1	1	1	1	1	1	1	1	0,5
seismic interventions	0,3			1	1	1	1	1	1	1	1	1	0
architectural components	0,15			0,7	0,7	0,7	0,4	0,7	0,7	0,7	0,7	0,7	0,4
plant components	0,1			0,5	0,5	0,5	0	0,5	0,5	0,5	0,5	0,5	0
state of maintenance	0,25			0,5	0	0	0	0,5	0,5	0	0	1	0
				0,204	0,1965	0,1965	0,168	0,234	0,234	0,1965	0,1965	0,2715	0,048
				0,387	0,394	0,307	0,328	0,623	0,636	0,307	0,332	0,695	0,089

FLOOD VULNERABILITY INDEX

	Weight	Cugliate-Fabiasco			Cunardo			Marchirolo		Bergamo	
		via Pagliolico 48	Via Torino 61D	Via S.Pietro 35B	Via Verdi 11	Via Pradonico 7	Via Prada 27	Via Baraggia 31	Via Statale 36	Bergamo Pre	Bergamo Post
Category 1	0,3										
residential type	0,08	0,5	0,75	0,75	0,5	0,75	0,5	0,5	1	1	1
year of construction	0,06	0,7	0,7	0,7	0,7	1	0,7	0,7	0,7	1	0,2
construction material	0,29	0,1	0,1	0,1	0,2	0,4	0,4	0,1	0,1	0,4	0,9
external walls cladding	0,12	1	1	1	0,8	0,8	0,1	1	1	0,8	1
interior walls material	0,1	0,4	0,4	0,4	0,2	0,4	0,4	0,2	0,2	0,4	0,2
internal walls cladding	0,17	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75
floor material	0,18	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
		0,106254	0,106506	0,106506	0,101754	0,12573	0,099954	0,100254	0,100758	0,12609	0,169638
Category 2	0,45										
number of floors	0,05	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
basement floor	0,25	1	1	1	1	0	1	1	1	1	1
ground floor elevation	0,25	1	1	1	0,2	1	1	1	1	0,2	0,2
floodable floor openings	0,14	0,7	0,7	0,7	0	0,7	0,7	0,4	0,4	0,85	0,7
presence of check valves	0,12	0,5	0	0,5	0	1	0	0,5	0,5	1	1
floodproofing measures	0,19	0,6	0,6	0,6	0,4	1	0,6	0,6	0,6	1	1
		0,35865	0,33165	0,35865	0,18045	0,30735	0,33165	0,33975	0,33975	0,3393	0,32985
Category 3	0,25										
electric plant position	0,2	0,2	0,2	1	0,2	0,2	1	0,2	0,2	1	1
plumbing plant position	0,15	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,2
thermal plant position	0,2	1	0,2	1	0,2	1	0,2	1	0,5	0,5	0
thermal plant typology	0,2	1	0,75	1	0,75	0,75	0,75	0,75	0,75	0,75	0
A/C plant position	0,15	0	0	0	0	0	0	0	0	0	0
emission terminals	0,1	1	0,1	1	0,1	0,1	0,1	0,1	0,1	0,1	0,9
		0,15375	0,07875	0,19375	0,07875	0,11875	0,11875	0,11875	0,09375	0,13375	0,08
		0,619	0,517	0,659	0,361	0,552	0,550	0,559	0,534	0,599	0,579

ENERGY EFFICIENCY INDEX

	Weight	Cugliate-Fabiasco			Cunardo			Marchirolo		Bergamo	
Category 1	0,165	via Pagliolico 48	Via Torino 61D	Via S.Pietro 35B	Via Verdi 11	Via Pradonico 7	Via Prada 27	Via Baraggia 31	Via Statale 36	Bergamo Pre	Bergamo Post
n-er of floors	0,35	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
S/V	0,25	0,5	0,5	0	0	0	0,5	0	0	0,5	0
WWR	0,4	0,5	1	0,5	1	1	0,5	1	1	0	0,5
		0,036609375	0,069609375	0,033	0,066	0,066	0,036609375	0,066	0,066	0,003609375	0,033
Category 2	0,375										
year of construction	0,25	0,6	0,8	0,6	0,4	1	0,4	0,8	0,8	1	0,2
ext wall stratification	0,18	0,2	0,2	0,2	0,5	0,75	0,2	0,2	0,2	1	0,2
Stratification of slabs	0,1	0,2	0,2	0,2	0,5	0,75	0,6	0,45	0,45	1	0,2
external wall cladding	0,05	1	0,2	1	0,2	1	0,2	1	1	0,2	1
type of window frame	0,18	0,25	0,25	0,25	0,5	1	0,75	0,5	0,5	1	0,5
Solar shading	0,15	0,5	0,5	0,5	1	1	0	0	0	1	0,5
EPC	0,09	0,55	0,95	0,55	0,95	0,95	0,75	0,95	0,95	0,95	0,15
		0,1595625	0,1768125	0,1595625	0,2158125	0,3470625	0,1531875	0,1899375	0,1899375	0,3583125	0,1254375
Category 3	0,46										
emission terminals	0,1	0,2	1	0,2	1	1	1	1	1	1	0,2
type of system regulation	0,1	1	0	1	0	0	0	0	0	1	0
DHW production system	0,15	0,5	0,5	0,5	0,5	0,7	0,5	0,5	0,5	0,7	0,7
renewable resources	0,2	0,4	1	0,4	1	0,4	1	1	1	1	0
type of heating system	0,05	1	0,7	1	0,2	0,7	0,7	0,7	0,7	0,7	0,7
A/C system	0,14	0	0	0	0	0	0	1	1	1	0,4
type of heat generator	0,2	0,8	1	0,8	1	1	1	1	1	1	0,4
mechanical ventilation	0,06	1	1	1	1	1	0,5	1	1	1	1
		0,2507	0,2001	0,1909	0,2001	0,2139	0,1863	0,2645	0,2645	0,3243	0,14766
		0,447	0,447	0,383	0,482	0,627	0,376	0,520	0,520	0,686	0,306

D Appendix D

FLOOD AND ENERGY INSPECTION SHEET

SCHEDA DI RILIEVO
EDIFICI RESIDENZIALI

INFORMAZIONI GENERALI

Dato	Rilievo	Note
Data del rilievo		
Codice ID edificio		
Regione		
Provincia		
Comune		
Indirizzo		
Coordinate		
Referente attività		

DOCUMENTAZIONE A DISPOSIZIONE

Dato	Rilievo	Note
Documentazione	○ Capitolato ○ Interventi manutenzioni ○ Attestato di Prestazione Energetica (APE) o rapporto di diagnosi energetica ○ Progetto dell’impianto termico/libretto di centrale	**Indicare documentazione disponibile scansionabile in loco**

	○ Altro (indicare: …………………………….)		
Disegni tecnici	○ Piantina ○ Prospetti	○ Sezioni ○ Altro	**Indicare Disegni disponibili scansionabili in loco**

CARATTERISTICHE TECNICO-COSTRUTTIVE EDIFICIO

Dato	Rilievo	Note
Descrizione area edificio		**Descrivere brevemente, anche con disegno, l'area in cui sorge l'edificio, se il terreno circostante è in piano, inclinato, etc.**
Schematizzazione edificio		**Disegnare uno sketch dell'edificio, con numero di piani e identificazione livelli, eventuale presenza di annessi (cantine, garage, etc.).** **Disegnare piante per ogni livello in assenza di documentazione**

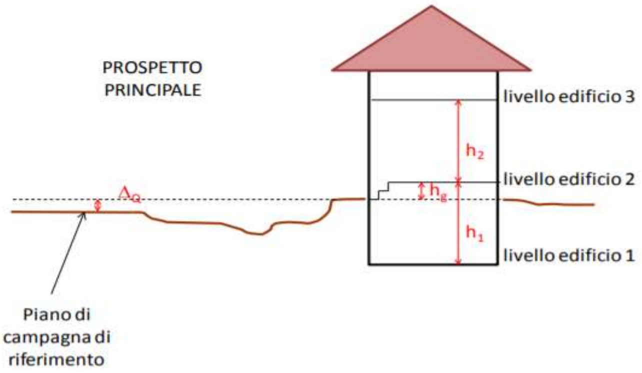
CARATTERISTICHE TECNICO-COSTRUTTIVE EDIFICIO

Tipologia edificio	○ **Casa singola** ○ **Villetta a schiera**	○ **Condominio** ○ **Casa di Corte**	
Anno di costruzione	○ Pre 1945 ○ Dal 1945 al 1973	○ Dal 1973 al 1991 ○ Post 1991	**Anno esatto:**
Stato di Conservazione	○ Ottimo ○ Normale ○ Scadente	Con normale si intendono i seguenti tipi di difettosità/deterioramenti: • deposizione di fuliggine o di particolato; • crescita biologica; • lievi deformazioni superficiali non associate a fessurazioni; • corrosioni superficiali;	

		• alterazioni del colore; Con scadente si intendono i seguenti tipi di difettosità/deterioramenti: • infiltrazioni/risalite di acqua; • corrosioni profonde; • carbonatazione; • fessurazioni; • distacchi e perdite di coesione degli strati di finitura o di altri elementi dell'involucro	
Tipologia Costruttiva	○ Struttura a pareti portanti ○ Struttura a telaio CA con muri tamponamento	○ Prefabbricati in legno ○ Altro	
Materiale Costruzione	○ Muratura ○ CA ○ Mista Muratura/CA	○ Legno ○ Pietra ○ Altro	
Superficie esterna			Specificare DOPPIO livello (appartamento e intero edificio) per la tipologia di interventi che posso effettuare

Copertura	**Tipologia:** ○ A falde ○ Piano ○ Altro. Specificare: Materiale ○ Legno ○ Metallico ○ Cemento ○ PVC ○ Altro. Specificare:	Indicare caratteristiche generali copertura (parte portante + tegole/pannelli etc)
Numero di piani		
Superficie interna	Livello I Livello 2 Livello 3 Livello 4+	
Presenza annessi	○ Sì ○ No Di che tipo? …………	
Presenza piano seminterrato	○ Sì ○ No	
	Se sì, a che utilizzo:	

	○ Cantina ○ Garage ○ Taverna ○ Lavanderia	○ Deposito ○ Abitazione ○ Altro	

Dato	Rilievo	Note
Quota di riferimento terreno [m slm]	**Quota:** **Coordinate:** **X =** **Y =**	Da remoto: DTM
Quote edificio	 ΔQ |_|_|_|_| m h_g |_|_|_|_| m h_1 |_|_|_|_| m h_2 |_|_|_|_| m	
Presenza bocche di lupo	○ Sì ○ No	
Presenza ascensore	○ Sì ○ No	
Altezza bocche di lupo		Rispetto alla quota di riferimento
Rivestimento muri esterni	**Elenca gli strati di rivestimento** ○ Intonaco non isolato ○ Mattoni o pietre faccia a vista ○ Intonaco isolato (isolamento a cappotto) ○ Gress ○ Altro (alluminio, etc.)	Da documentazione
Muri interni	**Perimetro m.i perimetrali** ○ Livello I ○ Livello 2 **Perimetro m.i divisori**	Da inserire solo per piani allagabili. Misurare dall'interno dell'edificio.

	○ Livello I ○ Livello 2	In caso di mancanza di disegni, misurare per ogni piano.
	Materiale muri divisori ○ Mattoni ○ CA ○ Cartongesso ○ Vetrocemento ○ Legno ○ Altro	Da inserire solo per piani allagabili
	Rivestimento muri interni ○ Intonaco ○ Ceramica ○ Carta ○ Legno ○ Altro	Da inserire solo per piani allagabili

	Materiale:	Superficie [m^2]	Livello
Pavimenti	○ Parquet		
	○ Moquet		
	○ Ceramica/gress		
	○ PVC/linoleum		
	○ Pietra (marmo/granito/altro)		
	○ Cemento		
	○ Resina (da verificare)		
	○ Altro		

Quadro Elettrico	○ Livello I ○ Livello II ○ > Livello II ○ Esterno. Specificare: Altezza Quadro Elettrico dal pavimento:	
Impianto idraulico	Presenza valvola di non ritorno ○ Sì ○ No ○ Non so	
Serramenti (Finestre)	Materiale: ○ Legno — n° = ○ PVC — n° = ○ Alluminio — n° = Altezza min dal pavimento: m Tipologia vetro ○ Singolo ○ Doppio ○ Triplo	Indicare l'altezza del I° livello non seminterrato
	Materiale — Numero	

Serramenti (Porte)	○ Legno ○ PVC ○ Alluminio	n° = n° = n° =	
Misure di Flood Proofing	Specificare quali:		

CARATTERISTICHE IDRAULICHE-ENERGETICHE EDIFICIO

Centrale Termica	○ **Livello I** ○ **Livello II** ○ **> Livello II** **Altezza Caldaia dal pavimento:**	
	Tipologia dell’impianto: ○ centralizzato ○ termoautonomo ○ teleriscaldamento	
	Tipologia generatori di calore • caldaia: ○ tradizionale ○ a condensazione ○ a biomassa ○ a pellet • pompa di calore • camino o stufe	Indicare marca e modello in caso di dubbio
	Potenza generatore di calore [kW]: Fonte di alimentazione:	
	Tipologia dei terminali di emissione del calore in ambiente: ○ Termosifoni/radiatori ○ Pannelli radianti a soffitto, parete o pavimento ○ Bocchette di diffusione di aria riscaldata/raffrescata ○ Termoconvettori a gas, acqua, elettrici	
	Tipologia del sistema di regolazione dell’impianto: ○ termostato ambiente in ogni appartamento, ○ regolazione climatica in centrale termica ○ valvola termostatica ○ altro	
	Tipologia impianto di produzione acqua calda sanitaria (ACS): ○ centralizzato (specificare se lo stesso utilizzato per riscaldamento o diverso) ○ termoautonomo (specificare tipologia: boiler, caldaia a gas, altro)	

	Presenza impianto di climatizzazione: ○ Sì N° = ○ No	
	Presenza impianti alimentati da fonti rinnovabili: ○ Sì Fonte: ○ No	
	Interventi di ristrutturazione per efficientamento energetico ○ Sì Tipologia Lavori - Anno: ○ No	

RILIEVO DANNI: LIVELLO I

Dato		Note
L'abitazione ha subito eventi alluvionali/allagamenti	○ Sì. Quante volte: ○ No Se sì, di che tipo: ○ Fluviale ○ Pluviale	
Altezza idrica	**Esterna h_e =** **Interna h_i =**	Rispetto quota di riferimento (esterna) e pavimento (interna). Specificare se più livelli
Piani allagati	○ Livello I ○ Livello II ○ Livello III ○ Altro	
Danni ai serramenti	○ Sì ○ No N° porte danneggiate Superficie danneggiata: m^2 Importo economico € N° finestre danneggiate Superficie danneggiata: m^2 Importo economico €	
Danni ai pavimenti	○ Sì ○ No Superficie danneggiata: m^2 Importo economico: €	

Danni agli impianti	○ Idraulico sanitario ○ Elettrico ○ Termico ○ Ascensore ○ Altro Importo economico: €	
Danni dovuti ad elevata velocità	○ Sì ○ No Specificare	
Danni agli arredamenti	○ Sì ○ No Importo economico €	
Danni a elettrodomestici di prima necessità	○ Sì ○ No Specificare Importo economico € ○	
Danni a motoveicoli	○ Sì ○ No Importo economico € ○	
Altro	Specificare Importo economico € ○	
Inagibilità	○ Sì ○ No Causa:	
Costi di clean-up	○ Sì ○ No Importo economico: €	
Azioni Intraprese	○ Nessuna ○ Uso di Pompe ○ Uso di Paratoie ○ Spostamento oggetti ai piani alti ○ Evacuazione ○ Altro Motivazione	

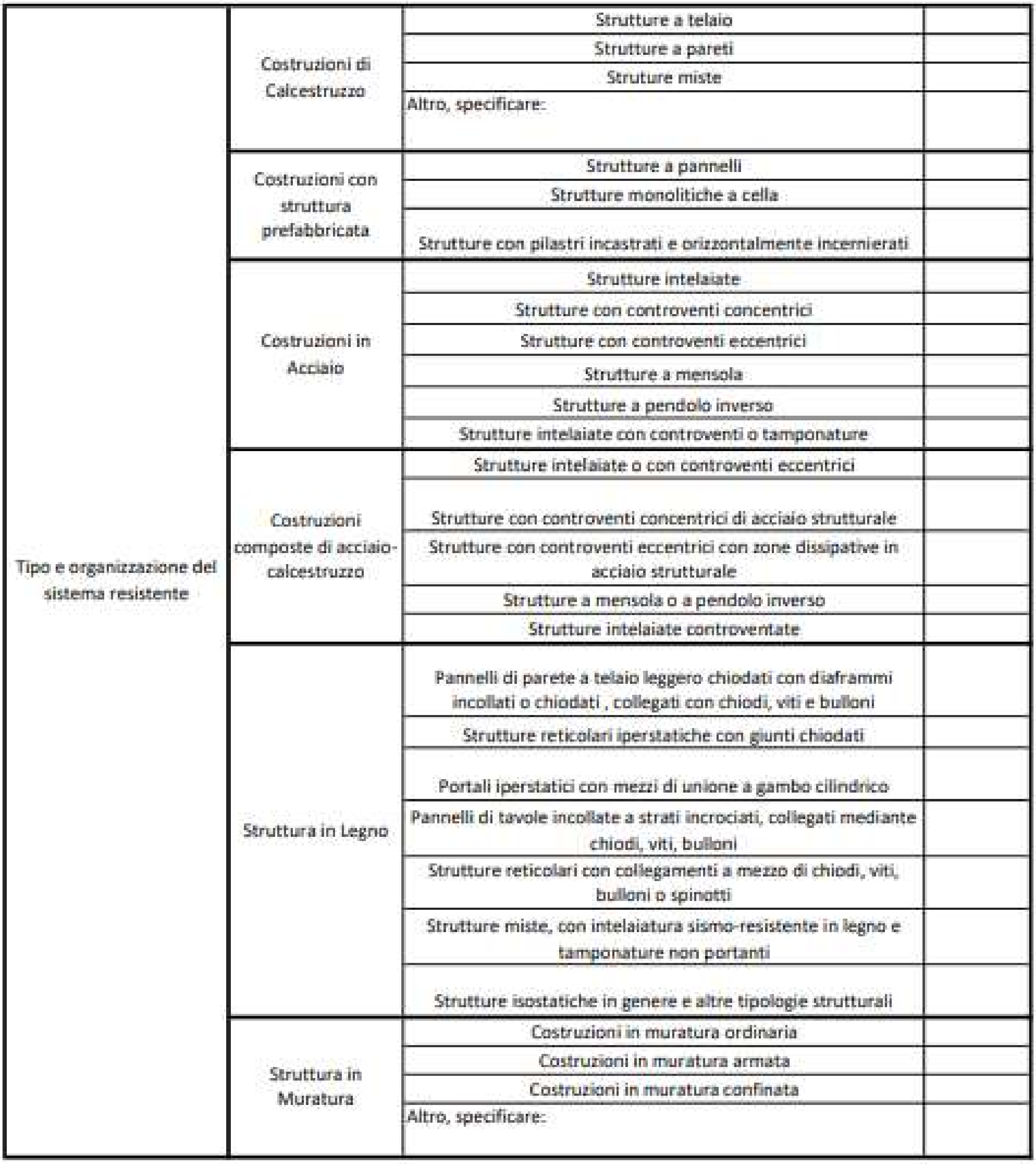
Documentazione allegata	○ Foto elementi danneggiati ○ Altro	

RILIEVO DANNI: LIVELLO II

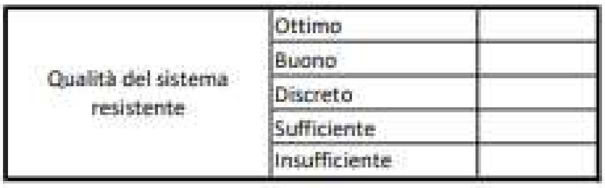
Dato		Note
L’abitazione ha subito eventi alluvionali/allagamenti	○ Sì. Quante volte: ○ No Se sì, di che tipo: ○ Fluviale ○ Pluviale	
Altezza idrica esterna	**Esterna h_e =** **Interna h_i =**	Rispetto quota di riferimento (esterna) e pavimento (interna)
Piani allagati	○ Livello I ○ Livello II ○ Livello III ○ Altro	
Danni ai serramenti	○ Sì ○ No N° porte danneggiate Superficie danneggiata: m^2 Importo economico € N° finestre danneggiate Superficie danneggiata: m^2 Importo economico €	
Danni ai pavimenti	○ Sì ○ No Superficie danneggiata: m^2 Importo economico: €	
Danni agli impianti	○ Idraulico sanitario ○ Elettrico ○ Termico ○ Ascensore ○ Altro Importo economico: €	

Danni dovuti ad elevata velocità	○ Sì ○ No Specificare	
Danni agli arredamenti	○ Sì ○ No Importo economico €	
Danni a elettrodomestici di prima necessità	○ Sì ○ No Specificare Importo economico € ○	
Danni a motoveicoli	○ Sì ○ No Importo economico € ○	
Altro	Specificare Importo economico € ○	
Inagibilità	○ Sì ○ No Causa:	
Costi di clean-up	○ Sì ○ No Importo economico: €	
Azioni Intraprese	○ Nessuna ○ Uso di Pompe ○ Uso di Paratoie ○ Spostamento oggetti ai piani alti ○ Evacuazione ○ Altro Tempo dell'azione: Ora Data • Motivazione	
Documentazione allegata	○ Foto elementi danneggiati ○ Altro	

SEISMIC INSPECTION SHEETS



Tipo e organizzazione del sistema resistente	Costruzioni di Calcestruzzo	Strutture a telaio	
		Strutture a pareti	
		Struture miste	
		Altro, specificare:	
	Costruzioni con struttura prefabbricata	Strutture a pannelli	
		Strutture monolitiche a cella	
		Strutture con pilastri incastrati e orizzontalmente incernierati	
	Costruzioni in Acciaio	Strutture intelaiate	
		Strutture con controventi concentrici	
		Strutture con controventi eccentrici	
		Strutture a mensola	
		Strutture a pendolo inverso	
		Strutture intelaiate con controventi o tamponature	
	Costruzioni composte di acciaio-calcestruzzo	Strutture intelaiate o con controventi eccentrici	
		Strutture con controventi concentrici di acciaio strutturale	
		Strutture con controventi eccentrici con zone dissipative in acciaio strutturale	
		Strutture a mensola o a pendolo inverso	
		Strutture intelaiate controventate	
	Struttura in Legno	Pannelli di parete a telaio leggero chiodati con diaframmi incollati o chiodati , collegati con chiodi, viti e bulloni	
		Strutture reticolari iperstatiche con giunti chiodati	
		Portali iperstatici con mezzi di unione a gambo cilindrico	
		Pannelli di tavole incollate a strati incrociati, collegati mediante chiodi, viti, bulloni	
		Strutture reticolari con collegamenti a mezzo di chiodi, viti, bulloni o spinotti	
		Strutture miste, con intelaiatura sismo-resistente in legno e tamponature non portanti	
		Strutture isostatiche in genere e altre tipologie strutturali	
	Struttura in Muratura	Costruzioni in muratura ordinaria	
		Costruzioni in muratura armata	
		Costruzioni in muratura confinata	
		Altro, specificare:	



Qualità del sistema resistente	Ottimo	
	Buono	
	Discreto	
	Sufficiente	
	Insufficiente	

Fondazioni	Fondazioni superficiali	
	Fondazioni su pali	
	Liquefazione*	

*Si manifasta per terremoti di magnitudo > 5.5 in terreni sabbiosi sciolti, posti sotto il livello di falda

Posizione edificio	Classificazione sismica	Zona 1	
		Zona 2	
		Zona 3	
		Zona 4	
	Caratteristiche della superficie topografica	T1: Superficie pianeggiante, pendii e rilievi isolati con inclinazione media i ≤ 15°	
		T2: Pendii con inclinazione media i > 15°	
		T3: Rilievi con larghezza in cresta molto minore che alla base e inclinazione media 15° ≤ i ≤ 30°	
		T4: Rilievi con larghezza in cresta molto minore che alla base e inclinazione media i > 30°	
	Categoria del sottosuolo	A: Ammassi rocciosi affioranti o terreni molto rigidi Vs > 800 m/s	
		B: Rocce tenere e depositi di terreni a grana grossa molto addensati o terreni a grana fina molto consistenti 3600 m/s < Vs > 800 m/s	
		C: Depositi di terreni a grana grossa mediamente addensati o terreni a grana fina mediamente consistenti 180 m/s < Vs < 360 m/s	
		D: Depositi di terreni a grana grossa scarsamente addensati o di terreni a grana fina scarsamente consistenti 100 ms < Vs < 180 m/s	
		E: Terreni con caratteristiche e valori di velocità equivalente riconducibili a quelle definite per le categorie C o D, con profondità del substrato non superiori a 30 m	
	dove possibile	frequenza di risonanza del suolo, calcolata in funzione del periodo proprio T = 4H/Vs ; f = Vs/4H	

Configurazione planimetrica *	Edificio regolare in pianta	
	Edificio non regolare in pianta	

* La distribuzione di masse e rigidezze è circa simmetrica rispetto a due direzioni ortogonali e la forma in pianta è compatta; Il rapporto tra i lati del rettangolo circoscritto alla pianta di ogni orizzontamento è minore di 4; Ogni orizzontamento ha una rigidezza tanto maggiore della rigidezza degli elementi verticali da poter assumere che la deformazione in pianta influenzi in modo trascurabile la distribuzione delle azioni sismiche tra questi ultimi e ha resistenza sufficiente a garantire l'efficacia di tale distribuzione.

Distanza		Indicarela distanza tra gli edifici	
		Eventuale presenza di giunti antisismici	
	Distanza massima murature	Per edifici in muratura non deve essere > 5 m	
		Altrimenti indicare massima distanza (luce solai)	

Configurazione in elevazione*	Edificio regolare in elevazione		
	Edificio non regolare in elevazione		
	dove possibile	frequenza caratteristica della struttura, da calcolarsi secondo metodi semplificati, qualora un modello dettagliato non sia disponibile T= 2π sqr(m/k) ; T1= C H^3/4 (EC8) ; f = n/10	

*tutti i sistemi resistenti alle azioni orizzontali si estendono per tutta l'altezza della costruzione o fino alla sommità della rispettiva parte dell'edificio; massa e rigidezza rimangono costanti o variano gradualmente dalla base alla sommità della costruzione (le variazioni di massa da un orizzontamento all'altro non superano il 25%, la rigidezza non si riduce più del 30% e non aumenta più del 10%); Eventuali restringimenti della sezione orizzontale avvengano con continuità da un orizzontamento al successivo o in modo che il rientro non superi il 10% dell'orizzontamento sottostante, né il 30% del primo orizzontamento.

Coperture	Spingente	Leggero	
		Medio	
		Pesante	
	Non Spingente	Leggero	
		Medio	
		Pesante	
	Spinta assorbita	Presenza di cordoli, catene, capriate, incatenamenti	
	Se nota, specificare la tipologia di copertura		

*da preferire una copertura leggera rispetto al materiale costituente l'edificio

Orizzontamenti	Solai in legno	Solai semplici	
		Solai a doppia orditura	
		Solai bidirezionali	
		Solai misti travi di legno e voltine	
	Solai in acciaio	Solette miste acciaio calcestruzzo (lamiera grecata)	
		Solai acciaio e tavelloni di laterizio	
		Profili in acciaio e lamiera grecata	
		Solai in acciaio a secco	
		Profili in acciaio e legno	
		Altro, specificare:	
	Solai in laterocemento	Solaio in opera	
		Solaio con travetti prefabbricati di CLS normale o precompresso	
		Solaio prefabbricato	
		Altro, specificare	

Elementi non strutturali	Componenti architettoniche	Pareti divisorie	
		Controsoffitti	
		Arredo fisso o mobile	
		Vetrate	
		Comignoli	
		Tegole	
		Decorazioni	
	Componenti Meccaniche, Elettriche e Impianti motori, tubazioni, condotte...	Pompe	
		Refrigeratori	
		U.T.A.	
		Ventilatori	
		Motori	
		apparecchiature elettroniche da appoggio o appese	
		Tubazioni e condotte	
	Altro, specificare:		
	dove possibile, formire la domanda sismica dell'elemento non strutturale, come indicato nelle NTC 7.2.3 : F = SW/q		

Stato di fatto	Da definire, per ogni caso specifico, l'effettiva corrispondenza tra lo stato di fatto dell'edificio e ciò che è riportato nei progetti. Identificare eventuali difformità o modifiche apportate negli anni. Se presente fornire l'opportuna documentazione	

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