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Ph.D. Thesis

Heat Waves Risk Assessment of Historic Urban Areas: Historic Buildings and their Urban Environment

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Because diversity is strength. Difference is a teacher. Fear difference, you learn nothing.

Hannah Gadsby

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Laura

Abstract

Climate change impacts such as extreme events and progressive global warming are threatening the conservation and liveability of urban cultural heritage. Understanding climate risks on heritage should be part of policy and planning decision-making processes to increase resilience and sustainability of both social and built environmental systems. However, despite a large body of literature focusing on climate-related hazards, there is a noticeable knowledge gap regarding a holistic conceptualization of the risks in historic urban areas, which is particularly noticeable in the case of the impacts of heat waves and heat urban island phenomena on urban heritage.

The scope of this thesis is to assess the impact and intrinsic characteristics of the area to determine risk, which serves as the basis for future prioritization of climate change adaptation interventions. The thesis develops a methodological approach for vulnerability and risk assessment supported by a multi-scale urban model that represents the interaction between urban spaces and heat waves via Geographic Information Systems (GIS) data. The methodology delivers a robust and replicable tool by using a categorization method for urban modelling that considers the vulnerability of historic areas both as urban systems and as heritage areas.

The MIVES (Integrated Value Model for Sustainability Assessment) methodology was applied, in order to provide decision-making with objective and justified prioritization. To frame a holistic approach, socio-economic, cultural, governance (services and resources) and physical (gathering tangible characteristics of all infrastructures, elements and buildings) aspects of the system are taken into account. The methodology is tested for its replicability in two case studies, the historic area of Bilbao, Basque Country, and the old quarters of Naples, Italy.

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1 Introduction

1.1 Background

The research of this dissertation has been undertaken mainly within the SHELTER project. SHELTER (Sustainable Historic Environments hoListic reconstruction through Technological Enhancement and community-based Resilience) is an EU-funded project that aims at developing a data-driven and community-based resilience improvement of historic areas.

As a way to give perspective on the background work on recent research, as well as projects on a European level on this subject and of the Shelter project, a review of previous and current state of the art on climate change risk and vulnerability assessment of cultural heritage and historic urban areas was undertaken.

1.2 Scope

The main objective of this research is to develop a risk assessment methodology for historic urban areas to heat waves, supported by a multi-scale urban model that represents the interaction between urban spaces, buildings and heat waves via Geographic Information Systems (GIS) data.

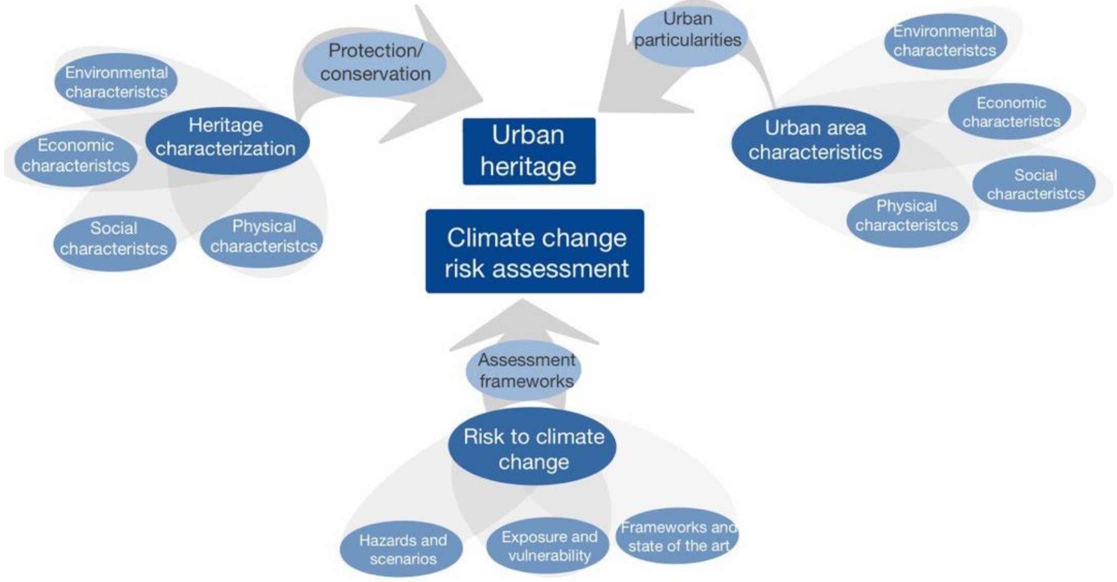


Figure 1. Areas of research considered in the doctoral thesis.

The methodology delivers a robust and replicable framework by using a categorization method for urban modelling that considers the vulnerability of historic areas both as urban systems and as heritage areas.

The following specific goals were set to reach the main objective:

- Review and analyse the state of the art of risk assessment to climate change for historic urban areas, and understand the needs and gaps in knowledge.
- Characterize heat waves and review the state of the art research for their impacts in historic urban areas, both in tangible assets and the degradation of materials and the economic and social impact for a holistic perspective.
- Develop a categorization method for building stock and public spaces representativeness supported via Geographic Information Systems (GIS) data model.
- Develop a set of indicators for the vulnerability and risk assessment of historic buildings and public spaces sustained by the use of objective and justified calculation models for the establishment of a priority index based on the MIVES methodology.
- Validate the methodology in two case studies of different scales, complexity and data availability to assess its replicability

1.3 Significance and need of the thesis

To set the goal and objectives for this thesis, a state of the art review was conducted in the beginning of the research, following a systematic approach. This review had the purpose of getting a global view of the risk assessment methodologies for heritage urban areas to climate change hazards, to understand the research needs on this area of study.

1.3.1 Methodology for the systematic review

Rationale and objectives

The systematic review (Berrang-Ford, Pearce, and Ford 2015) with consequent meta-analysis of the results follows the PRISMA-P protocol (Moher et al. 2015; Xiao and Watson 2017). The research question driving the systematic review was: *what risk or vulnerability assessment methodologies have been developed for historic areas against climate change?*. A critical analysis and evaluation of the approaches and scope of each methodology found concluded in the identification of the knowledge gaps.

The climate change related hazards were selected following those addressed by the IPCC (IPCC 2022). Extreme precipitation is not included in the search, as floods are its main consequence and preliminary searches showed that the results were repetitive. Impacts or consequences of the hazards were not considered in the selection of keywords e.g. spread of microorganisms due to the change in climate conditions, changes in human patterns, as a review on this subjects would require an in depth analysis of each of them.

1.3.2 Search strategy

The searches were conducted using Scopus and Web of Science databases in November of 2020, which looked up the keywords included in the title, keywords and abstract. Due to language limitations, only the literature with keywords in English was included. The search included articles (included in journals and books) and conference proceedings that were accessible through the databases mentioned.

Consequently, and considering all the previously formulated research questions, the keywords for the search were selected as the combinations of keywords shown in Table 1, with the asterisk signaling that the endings to some of their root words might vary.

<table>
<tr><td rowspan="10">Risk assess*
OR
Vulnerability assess*</td><td rowspan="10">AND</td><td colspan="3">Climate change
OR</td><td rowspan="10">AND</td><td rowspan="10">Heritage
OR
Historic area</td></tr>
<tr><td>Heat wave</td><td rowspan="9">AND</td><td rowspan="9">Climate change</td></tr>
<tr><td>OR</td></tr>
<tr><td>Cold wave</td></tr>
<tr><td>OR</td></tr>
<tr><td>Flood*</td></tr>
<tr><td>OR</td></tr>
<tr><td>Storm</td></tr>
<tr><td>OR</td></tr>
<tr><td>Sea level rise</td></tr>
</table>

Table 1. Combinations of keywords used in the systematic search.

1.3.3 Eligibility criteria

The different combination of keywords in both platforms produced 616 total results; many of them were repeated in the different searches. A first filtration through title and abstract was limited to the identification of the literature related to the subject, excluding the ones from other areas of study and following the criteria stated in Figure 2. The results were then reviewed individually through the abstract and full text to determine if they actually defined a risk assessment methodology or considered climate change related hazards and their impact on cultural heritage. For this filtration, it was analyzed if (a) they followed a methodology that characterize risks and assess their magnitude following a specific and accepted method and (b) considered climate change related hazards. It is important to clarify that as mentioned in the rationale only studies considering the hazards considered by the IPCC were included, not considering articles that tackled other hazards e.g. earthquakes, subsidence, and so on, that are not considered directly related to climate change.

This systematic evaluation led to 29 papers that were assessed in detail within this study. These selected papers were reviewed in their entirety and classified in relation to the hazard addressed and the risk-assessment elements of the IPCC approach that were considered (hazard, exposure, vulnerability). The year of publication was also analyzed to detect the rates of interest in the subject over time.

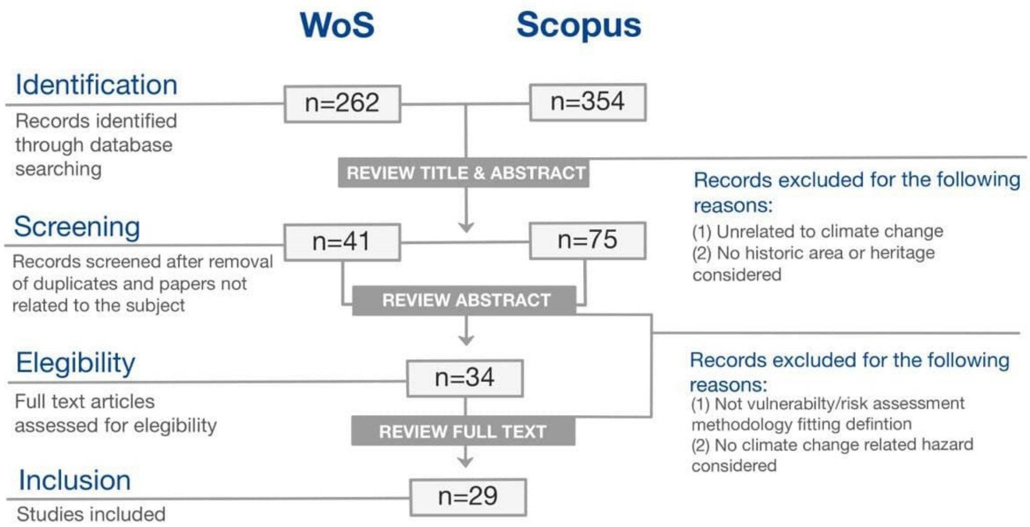


Figure 2. Literature search and evaluation for inclusion in the critical review (adapted from [6]).

In this process, information on the articles was entered on a spread sheet and sorted by publication data (year, title, author, source, DOI) and the results of the critical analysis were focused on the type of hazard addressed, the aspects of risk (hazard, exposure, vulnerability) and the socio-economic, cultural, governance and physical systems within the historic urban areas.

Following the conclusions drowned from the research questions, the review will be divided into three parts: starting with an analysis of the hazards addressed by the studies, followed by the risk aspects and systems assessed, to finish with an overview of the interest in the subject looking at the publication dates of the selected literature.

1.3.4 Meta-analysis.

Hazards

As mentioned, a key parameter when reviewing the different methodologies was the climate change related hazard and climatic driver considered in each model. As previously established, cold waves, heat waves, floods deriving either from sea level rise, storms or heavy precipitation events are all among the hazards that were researched. Even if wildfire was not a specific keyword derived from the hazard selection, a study was found through the searches with climate change as keyword, and included in the review as it is a hazard derived from climate change.

Once the search results had been filtered for suitability with the established criteria, a total of 29 papers were identified. Having sorted the papers according to the hazard addressed in the methodologies developed in each research work, it was observed, as shown in Figure 4, that flooding was the most studied hazard with a total of 22 flood-related methodologies. These studies include flooding from rising sea level and storms (Bernardini et al. 2019; D'Ayala et al. 2020; Kaspersen and Halsnæs 2017; Kittipongvises et al. 2020; Miranda and Ferreira 2019; Reeder-Myers 2015; Reimann et al. 2018; Sanchez, Sanchez, and Ribalaygua 2020; Sardella et al. 2020; Elena Sesana et al. 2020; Vojinovic et al. 2016; Ezcurra and Rivera-Collazo 2018; Ferreira and Santos 2020; Figueiredo, Romao, and Pauperio 2020; A Gandini et al. 2020; A Gandini, Garmendia, et al. 2018; Alessandra Gandini et al. 2018; Garrote et al. 2020; Iosub, Enea, and Minea 2019). Moreover, floods are analyzed in combination with other hazards in the three multi-hazard methodologies found in the search, along with global warming (Kotova et al. 2019), non-climate change related hazards such as earthquakes, landslides and wind (Ravankhah et al. 2019) and higher global temperatures (Forino, MacKee, and von Meding 2016).

In all, seven of the 29 studies found in the review considered that the general change in climate caused by climate change was a hazard (Kotova et al. 2019; Forino, MacKee, and von Meding 2016; Hao et al. 2019; Bosher et al. 2019; Rajčić, Skender, and Damjanović 2018; Alessandra Gandini, Garmendia, and San-Mateos 2017; Leissner et al. 2015) and one wildfire-specific methodology was found (Mallinis et al. 2016).

Finally, no search results were found on either cold waves or on heat waves; the general climate change search results fared no better at including either of those hazards. Therefore, as shown in Figure 3, taking into consideration the climate change-related hazards among the 29 studies, three of which were multi-hazard, floods were analyzed in 22 methodologies, the general change in climate in eight, and wildfires in one.

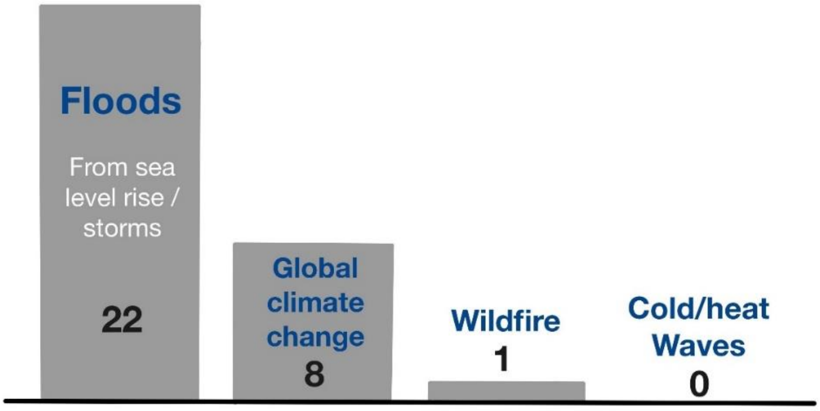


Figure 3. Number of methodologies that consider each hazard.

Risk aspects and systems within the studies

Following the IPCC approach, the methodologies were reviewed to identify the risk-assessment aspect and the particularities of the historic urban areas that they evaluated. The analysis carried out for this review breaks down the results into three groups: (i) studies that only characterize hazard likelihood and severity, (ii) methodologies that also consider exposure, and (iii) studies that, besides hazard and exposure assess the vulnerability, differentiating between sensitivity and coping capacity (see Figure 4).

Hazard likelihood and severity were considered in seven of the methodologies under analysis [54,56,59,66–68,71], and exposure of the elements was only included in the analysis of one methodology [75].

Several studies mentioned vulnerability, but on further analysis, it was verified that only sensitivity indicators and not coping capacity indicators had been applied. Therefore, the analysis distinguishes between studies that considered sensitivity (10 studies), and the ones that included sensitivity and coping capacity indicators (11 studies).

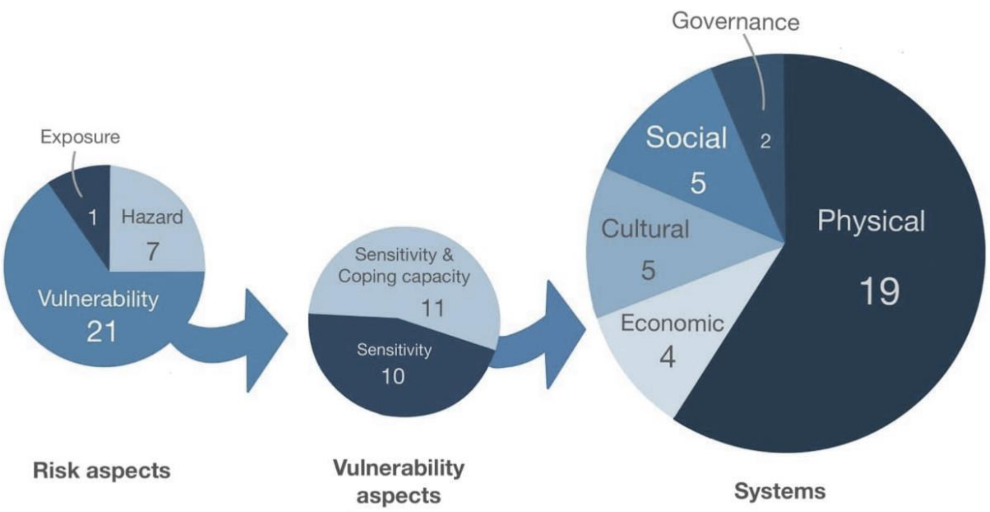


Figure 4. Number of methodologies that consider risk and vulnerability aspects and the systems analyzed.

The characteristics of historic urban areas were considered in the vulnerability assessment methodologies that were organized into five systems: social, economic, cultural, governance (services and resources) and physical (gathering tangible characteristics of all infrastructures, elements and buildings).

Reviewing the systems included in the vulnerability assessment methodologies (see Figure 3), 19 of the 21 methodologies included physical vulnerability, which was the sole focus of 10 to the exclusion of other systems, [49,52,53,60,65,69,70,72,74,76]. One was specifically focused on governance vulnerability [57], and another one, on social vulnerability [48]. With respect to the eight studies on the vulnerability of various systems, all included physical vulnerability along with cultural [58,62], social and economic [58,64,77], governance [51] and social and economic aspects [50].

Therefore, the most common combination found in the review was the assessment of physical vulnerability to flooding [49,52,53,55,60,61,65,66]. It should be also highlighted that cultural vulnerability evaluated in terms of the cultural value of the asset has only been addressed in five papers, all focused on flooding (see the various papers by A. Gandini, and one by Vojinovic *et al*. 2016) (A Gandini, Prieto, et al. 2018; Alessandra Gandini, Garmendia, and San-Mateos 2017; Alessandra Gandini et al. 2021; Vojinovic et al. 2016).

1.3.5 Identification of gaps and future research needs

Starting with the hazards caused by climate change, the critical review is clear in determining that there is a large body of literature in WOS and Scopus addressing flooding (76%), from either sea level rise or storms, and the consequences of climate change are considered in a high number of studies (28%). Other important hazards are rarely or not present in the literature (fire 3%, cold and heat waves none). Therefore, future research should focus on less studied hazards, such as heat waves, even though it is a worldwide hazard with high impact on the built environment and citizens, represents a clear gap in knowledge.

With respect to the vulnerability and risk-assessment methodologies, the vulnerability of urban environments is frequently linked in the literature to their physical, cultural, socio-economic and governance systems, depending on characteristics such as geographical position, materials, urban plot and morphology, wealth, population age, etc. These characteristics will constrain the severity of the resulting impacts. In the case of historic urban areas, as seen in this review, there is a close focus on the physical vulnerability of the built environment (62% of the papers) while social vulnerability is addressed in 14% of the papers, economics in 14%, cultural matters in 14% and governance in 7%, showing very few studies of relevance on cultural, socio-economic and governance vulnerability. Therefore, climate change related impacts on historic areas depend on the complex relationships between physical, social, economic, and cultural aspects, and all these systems have to be considered when assessing the foreseeable hazards. Hence, the research on more holistic risk assessment approaches is fundamental to defining the path that the ongoing research work should follow. Furthermore, research into less studied hazards, such as heat waves is a necessary next step in the field.

1.4 Analysis of research at a European level

This section seeks to identify relevant research projects at a European level, so as to evaluate research activities developed for climate change risk and vulnerability assessment of cultural heritage and historic urban areas. The projects were identified during the literature review, and later completed with a search in CORDIS, the European Commission's public repository of information on all EU-funded research projects. This search was conducted as a literature search, as it encompassed projects relating both to cultural heritage and to climate change.

In total, 9 projects were identified and analyzed. For this process, the projects were organized in a spread sheet in chronological order, with columns containing the administrative data (duration and coordinating partners and countries) and the relevant details for the review: hazards under consideration and systems under analysis when assessing climate-change-related risk.

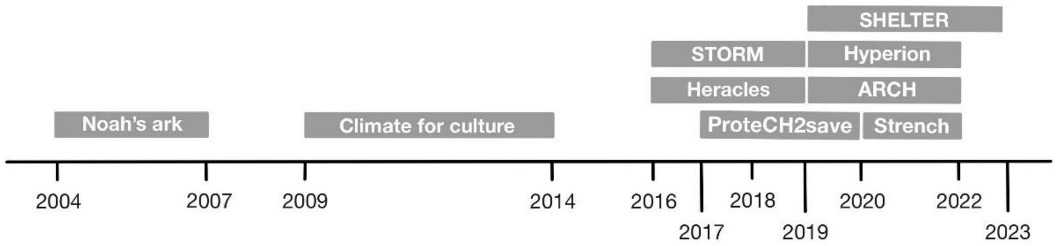


Figure 5: Timeline of EU research projects focused on climate change risk and vulnerability assessment of cultural heritage/historic urban areas.

The nine projects are identified in chronological order (Figure 5), starting with Noah's Ark in 2004, still a reference in climate change impact on cultural heritage. The project was focused on material weathering and, therefore, on physical vulnerability, and addressed the main hazards of climate change by analyzing changes to precipitation, wind and frost patterns. Its final report was "The Atlas of the Impact of Climate Change on European Cultural Heritage: Scientific Analysis and Management Strategies" (Sabbioni et al. 2010), which is focused on the development on a European scale of “climate risk and vulnerability” maps for built heritage.

The Climate for Culture project was initiated in 2009, two years after the start of the Noah's Ark project. The changing temperature patterns caused by climate change were considered as the main hazard. The main results and conclusions were summarized in the final project report with maps of future physical climate-induced risks for historic buildings and their interiors. It included a chapter on risk assessment, focusing on the different envelope materials and considering mechanical, chemical and biological degradation mechanisms (Leissner et al. 2015).

Noah's Ark and Climate for Culture were therefore the pioneer projects on the impact of climate change on cultural heritage within Europe. Neither addressed extreme climate-change related events, but changes to overall climate and weather patterns. Both projects preceded the seven projects that were to follow, starting in 2016 within the Horizon 2020 program of the European Commission.

Heracles and Storm, both of them finished in 2019, focused on the physical impact of climate change and consequential extreme events on the built heritage. Heracles, focusing on climate change effects on artefacts and archaeological sites, developed *an in-situ* diagnostic protocol for quick assessment and monitoring of the weathering state and its progress; considering alongside physical risk and social vulnerability. Heracles, on the one hand, contemplated the general change in climate alongside the risk of flooding, due to storms and sea-level rise. Storm, on the other hand, researched how different vulnerable materials, structures and buildings are affected by different extreme weather events together with risks associated with climatic conditions and natural hazards via monitoring.

In 2017, the project ProteCHt2save was launched, finishing in 2020. Its focus was primarily on floods and heavy rain events as well as droughts due to extreme heat, focusing on built heritage and the identification of risk areas and physical vulnerabilities.

As can be seen in the Figure 5, four projects have recently been launched between 2019 and 2020 and are currently in progress. All of them are focused on risk management and assessment and seek to develop different tools and strategies. While the previous projects were mainly focused on physical vulnerability, after 2019 there was a shift to a more holistic approach. Simultaneously, there was a change of focus from general climate change to extreme events, with all of the projects currently under development considering most of the major climate-change-related hazards mentioned in the IPCC reports (IPCC 2014b); such as storms, sea level rise, extreme precipitation and heat and cold waves.

ARCH aims to develop a disaster-risk management framework for assessing and improving the resilience of historic areas to climate change and associated natural hazards, including impact and risk assessment methodologies with holistic approaches that account for governance and physical characteristics. Hyperion, on the other hand, is focused on multi-hazard modelling, analysis of building materials and deterioration processes, likewise considering policy tools and economic resilience.

The Shelter project launched in 2019 with the goal of developing a risk assessment methodology, among multiple other outputs, to address multiple hazards through a holistic vision that considers cultural, environmental, economic, social and governance systems together with the physical vulnerability of the historic built environment.

Finally, the Strench project, launched in 2020, was oriented towards the development of tools for assessing climate change effects, including a vulnerability ranking for multiple climate-change-related hazards (flood, landslides, windstorm, heavy rain and fire).

Table 2 shows the main characteristics of relevance to the review of the EU research projects, namely hazards and systems; together with the coordinating entity and the years they took place.

PROJECT	COORDINATOR	YEARS	HAZARDS	SYSTEMS
NOAH'S ARK	Consiglio Nazionale delle Ricerche (IT).	2004-07	Change in climate, precipitation, wind and frost patterns.	Physical vulnerability (weathering of materials).
CLIMATE FOR CULTURE	Fraunhofer Institute (GE).	2009-14	Change in climate (mainly change in temperature patterns).	Physical vulnerability.
HERACLES	Consiglio Nazionale delle Ricerche (IT)	2016-19	Change in climate and flooding, due to storms or sea level rise	Physical vulnerability (artefacts and archaeological sites)
STORM	Engineering - Ingeniería Informatica SPA (IT)	2016-19	Change in climate, flooding, wildfire and landslides.	Physical vulnerability (buildings, structures, materials)
PROTECHT2-SAVE	Consiglio Nazionale delle Ricerche (IT)	2017-20	Floods, heavy rain, droughts	Physical vulnerability (built heritage)
ARCH	Fraunhofer Institute (GE)	2019-22	Change in climate, floods, heatwaves, wind and landslide	Governance and physical vulnerability
HYPERION	Institute of Communication and Computer Systems (GR)	2019-22	Climate change, floods, wind, landslides and fire	Physical, governance and economic vulnerability
SHELTER	Tecnalia Research & Innovation (ES)	2019-23	Climate change, floods, extreme precipitation, heat and cold waves, earthquakes and subsidence	Cultural, environmental, economic, social, governance and physical vulnerability
STRENCH	Consiglio Nazionale delle Ricerche (IT)	2020-22	Flood, landslides, windstorm, heavy rain and fire	Holistic approach

Table 2. Main characteristics of the European research projects.

1.5 Research Methodology

The research developed in the framework of this thesis is based on some of the advances in the fields of knowledge under consideration, and combines them in order to create a new comprehensive approach to vulnerability and risk assessment for historic areas under heat wave conditions.

First, the problem was defined and a literature review was conducted to understand how previous research has addressed and proposed solutions to the specific problem under study and to understand the needs and gaps in the field. In a second step, the requirements for a methodology were identified and established and finally, the solution was designed, by mixing different alternatives and methods and by creating a new and ad hoc methodology for the assessment.

Research was based on the following hypothesis:

- The use and design of tailored multiscale information models can support vulnerability and risk assessments of historic cities and decision-making on adaptation strategies;
- The use of objective decision-making models can create evidence by determining comparable results and indexes, in order to prioritize areas or buildings where adaptive solutions are needed;
- A decision-making methodology for the risk assessment of historic buildings at urban level, based on different levels of information and proper modelling strategies, can be cost effective, reaching a balance between accessible information and accurate results.
- The need for robust and replicable methodologies, which allow decision makers to become familiar with it and use it regularly.

1.6 Main contributions to the subject

As a result of the state of the art review this thesis has as a goal to provide three main contributions; a categorization framework for historic urban areas based on their vulnerability to heat waves, a holistic risk assessment methodology, and two models for the validation of the robustness and replication capacity of the methodology

1.7 Structure of the thesis

The thesis is structured in seven chapters:

Chapter 1. Introduction. This first chapter starts by analysing the need for the thesis via a state of the art review that provides the perspective for the need and significance of the research. It also presents the scope and methodology of the research, and moves on to set the objectives and structure for the document.

Chapter 2. Conceptual framework. The second chapter provides the overall view on the state of the knowledge the different thematic areas on which the methodology is built and their interrelations. It presents the concepts and approach to climate change, heat waves, risk assessment and cultural heritage as well as tools and methods used for the data management and urban modelling, and how they are considered and applied along the research and dissertation.

Chapter 3. Methodological approach. This section of the dissertation develops and explains the methodology for the risk assessment and the management of data and the model. The first part encompasses the vulnerability assessment and the development of the indicators by combining the research on the different areas of knowledge mentioned on the second chapter. The second part encompasses the use of a GIS model and the data management for the implementation of the methodology and development of risk indexes.

Chapter 4. Validation of project results in an open lab (Bilbao). The forth chapter addresses the implementation of the developed methodology on the case study of Bilbao (Spain). It considers the area of the old quarters, a small area in which the methodology can be thoroughly tested both using the categorization developed in chapter 3 and real data.

Chapter 5. Validation of project results in an open lab (Naples). This fifth chapter of the dissertation addresses the case study of Napoli (Italy). The case study considers the historic centre of Naples, encompassing a larger and more complex area with more limited access to data that tests the robustness and replicability of the methodology.

Chapter 6. Conclusion and future perspectives. This last main chapter of the thesis gathers the most significant conclusions of the research, providing the afterthoughts on the contribution of the methodology to the prioritization of future interventions and the conservation of historic urban areas against climate change. In addition, the chapter provides a reflection on the future research work on the subject for the selection and implementation of solutions against heat waves on historic areas and other urban areas.

Chapter 7. Bibliography. Gathers the bibliographical references resulting from the documental research within the scope of this thesis.

2 Conceptual framework

2.1 Climate change

According to the fifth assessment report of the IPCC, the global average temperature will increase 0.3-0.7ºC before 2035 and 2ºC by the year 2100. Global warming and climate change may be inevitable, and experts locate the maximums in temperature in urban centres and their areas of influence (IPCC 2014a). This rise in temperature added to the increasingly numerous and extreme precipitation events and subsequent flood events, sea-level rise and the increasing frequency and intensity of heat waves and other environmental disasters, poses serious challenges for urban areas. Therefore, this highlights the need for and the importance of risk assessment methods for the prioritization of adaptation strategies and development towards more resilient cities. For this purpose, several of the United Nations Framework Convention on Climate Change's (UNFCCC) Conference of the Parties (COP) have highlighted the need to establish a global goal on adaptation of urban areas "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change (UNFCCC 2015). Within this context, and in the complex systems that are cities, historic urban areas (HUA) are singular from a vulnerability and resilience perspective (Longworth 2014; Fatiguso et al. 2017; Brabec and Chilton 2015), due to their specific characteristics and importance, which makes mandatory specific approaches for the development of risk assessment methods and adaptation strategies.

At its 29th session in 2005, The World Heritage Committee, recognized climate change as an emerging threat to the conservation of many cultural and natural sites, and the UNESCO World Heritage Centre, in its report on climate change and World Heritage (World Heritage Committee 2006) recognizes climate change as one of a range of factors affecting natural and cultural heritage. Furthermore, the IPCC recognises that the destruction of Heritage will be a part of the overall impacts of climate change, including damage to the physical fabric and a loss of traditional practices and the overall sense of place (IPCC 2014a).

Cultural heritage is the bond with the past living in the present, it forms the way of thinking and building identity, our relationship with the environment and the places we live in (Harrison 2010). When assessing the risk caused by climate change to cultural assets, there has been a more tourism-based approach when analysing historic areas, approaching heritage predominantly as a resource for economic development, and primarily focused on UNESCO World Heritage Sites. Nevertheless, in the current climate crisis, it is mandatory a broader perspective to approach heritage. When analysing the risk of a changing climate, and derived extreme hazards, heritage needs to be understood as a cultural capital of the communities (Adger et al. 2013), as it is key in the process of developing a sustainable relationship between people and their environment, strengthening the sense of belonging and the sense of place (Brabec and Chilton 2015). Therefore, cultural heritage is an essential resource for sustainable development and for the elaboration and implementation of successful strategies to manage the impact of climate change. This fact is reinforced by the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs) adopted by the UNGA (United Nations General Assembly) in September 2015 (UN General Assembly 2015) when it addresses cultural heritage in the context of sustainable development, with Target 11.4 of the SDGs calling for “strengthening efforts to protect and safeguard the world’s cultural and natural heritage”, and Goal 13 calling for taking “urgent action to combat climate change and its impacts”.

When developing strategies to protect cultural heritage or urban areas from any environmental hazards, risk assessment is an essential step. While the impacts of current and future climate change on natural systems, socio-economic systems, and on urban systems, in general have been well documented (IPCC 2022), there has been little research of climate impacts on cultural heritage or historic areas (Quesada-Ganuza et al. 2021), with the main body of literature on the subject focused on impacts on materials, and mainly on World Heritage Sites (Bigio, Ochoa, and Amirtahmasebi 2014) and tangible heritage. Despite the high level of interest in climate change impacts on heritage; and the abundance of literature addressing the need for research in the area (Brabec and Chilton 2015; Quesada-Ganuza et al. 2021; E. Sesana et al. 2021), methodologies for the understanding of the impacts of climate change on cultural heritage and historic areas with a holistic approach (considering all aspects of intangible and tangible heritage within the urban system) are a noticeable gap in knowledge (Quesada-Ganuza et al. 2021). As analysed on the first chapter of this dissertation, although they are some examples of methodologies that consider the more traditional threats, as earthquakes and floods, there has not been a risk assessment approach to the impact of heat waves and the urban heat island phenomenon on cultural heritage (Quesada-Ganuza et al. 2021).

2.2 Heat waves and heat islands

One of the main hazards that impact on urban areas are heat waves, and the probability and intensity of extreme heat waves have been increasing over many parts of the world owing to climate change (Meehl and Tebaldi 2004; IPCC 2018). Heat waves are a concerning hazard for urban population since the risk from them will worsen for cities and infrastructure (IPCC 2022), with a minimum of half of the world's population, considering the best case RCP 2.6 scenario, exposed to extreme periods of heat and humidity this century (Q. Zhao et al. 2021).

There is no universal definition for heat waves, different dentitions and thresholds vary depending on the region and climate. As a general definition, the World Meteorological Organization (WMO) guidance on heat-health warning (WMO-No.1142) (World Meteorological Organization 2018; UNEP and WMO 2007) defines heat waves as periods of unusually hot and dry or hot and humid weather that have a duration of at least two to three days and a discernible impact on human activities (Jarosińska et al. 2018). Such extreme events associated with particularly hot sustained temperatures produce important impacts on human mortality, economy, and ecosystems (Meehl and Tebaldi 2004; IPCC 2022). Two well-documented examples are the 1995 Chicago heat wave and the Paris heat wave of 2003 (De Ridder et al. 2016; Lobo, Maisongrande, and Coret 2010). In each case, severe hot temperatures contributed to human mortality and caused widespread economic impacts, inconvenience, and discomfort. Global climate projections that consistently point towards an increase in the number, frequency, and intensity of heat waves (Meehl and Tebaldi 2004; Schär et al. 2004; De Ridder et al. 2016) have shown that extremely hot summers such as the one of 2003 in Europe are likely to become fairly common towards the end of the century.

When assessing heat waves in urban areas, the urban heat island (UHI) phenomenon has to be taken into consideration. The urban heat island effect shows how morphology of an urban area affects heat, as shading and ventilation, the constructive and technical physical-chemical characteristics of urban elements and materials and the type and distribution of green spaces influence its intensity (Li and Bou-Zeid 2013; Oke et al. 2017). Urban geometry and materials influence wind flow, energy absorption, and the ability of surfaces to release long wave radiation back to space (Gartland 2010; Oke et al. 2017) causing the urban heat island effect [Figure 6]. Heat waves amplify the urban heat island effect (Matthaios Santamouris 2019), and combined with the increase on urban population and growth of the built environment, it will potentially affect half of the human population in the future (L. Zhao et al. 2018; Huang et al. 2019).

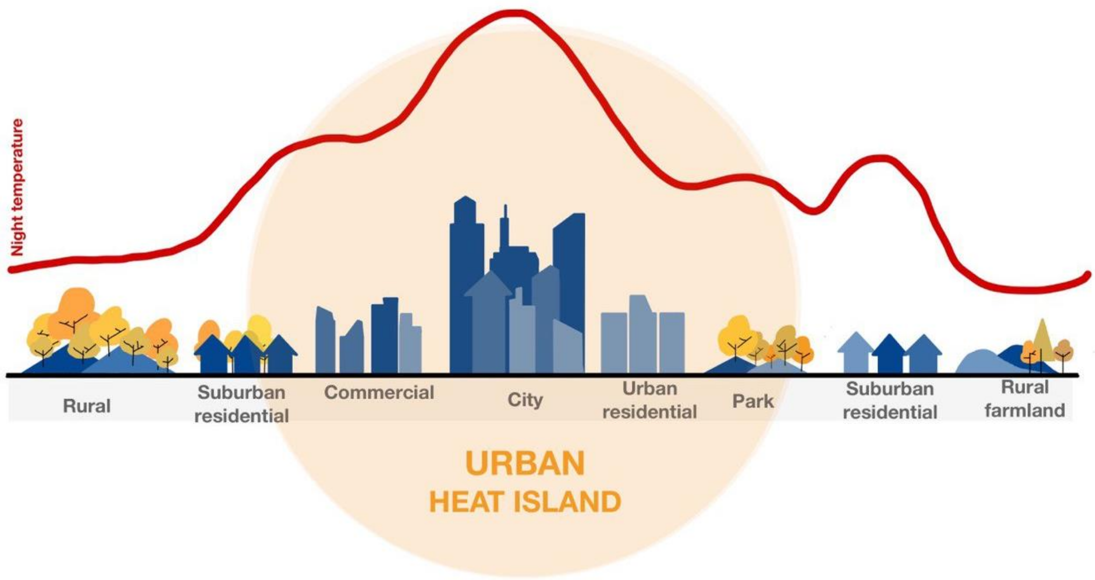


Figure 6. Graph showing UHI- linking temperatures urban morphology and land uses classification. Adapted from (WMO 2015).

Other than the proven and well researched consequences of high urban temperatures and heat stress for human health (IPCC 2022), and their influence in mortality (He et al. 2021; IPCC 2022), is a main concern for the urban environment when considering heat is their effect on the reduction of thermal comfort, inside buildings and in urban environments. Thermal comfort is the key indicator that describes the subjective temperature experience that each person has, combining the impacts of solar radiation and shade, wind, air temperature and relative humidity on thermal sensation. The indoor thermal comfort depends on building characteristics such as thermal resistance and thermal mass of the envelope, ventilation and shading, added to aspects related to the orientation and geographical position [Figure 7]. In the case of heat waves, thermal comfort within urban spaces is a fundamental factor (He et al. 2021) that increases the effects of the climatic conditions. One of the main consequences of this phenomenon on the built environment is the increase on energy consumption (Matheos Santamouris, Cartalis, and Synnefa 2015; Matthaios Santamouris 2019) and the consequential thermal inequality (Mitchell and Chakraborty 2015). Increased urban temperatures are also documented to affect the environmental quality of cities increasing the level of tropospheric ozone (Pyrgou, Hadjinicolaou, and Santamouris 2018; Matthaios Santamouris 2019) and affecting the air flow, causing an increase of the harmful atmospheric pollutants (Stedman 2004; Czarnecka and Nidzgorska-Lencewicz 2014).

2.3 Historic Urban Areas

ICOMOS, in the Washington chapter 1987 (ICOMOS 1987), defines historic urban areas as cities, towns and historic quarters, along with their natural and artificial environments, that besides their role as historical records, reflect the values of traditional urban cultures, and are formed by a historical layering of values that have been produced by an accumulation of traditions and experiences of diverse cultures. Introduced in the UNESCO Vienna memorandum of 2005 (UNESCO 2005), and developed in the subsequence recommendations of UNESCO and ICOMOS, the concept of Historic Urban Landscape (HUL) has built on the historic urban area definition of 1987, including a more holistic approach, and addressing the importance of intangible heritage. Within this 2005 definition, the carriers of significance in historic urban areas were expanded from traditional values as the historic building fabric, urban grid and spatial qualities of the public space to such intangible concepts as traditional land use, associative communal memories, rituals, and the patterns of historic urban evolution (Araoz 2008). Therefore, historic cities are a net of tangible and intangible heritage, and are, within any urban area, the places that carry most of the identity and sense of belonging of the community (Adger et al. 2013).

As referred to in the UNESCO recommendation on HUL in 2011 (UNESCO 2011), the present and future urban conservation policies, urgently require a new generation that identifies and protects historical stratification and the balance of cultural and natural values in urban settings. For this purpose, it is necessary a proper risk assessment methodology that considers the challenge of climate change and prioritizes the more vulnerable assets when developing protection strategies and policies.

The creation and categorization of heritage is a process involving an institutionalised, top-down planning process that creates an “official heritage”, and the bottom-up “sense of place” that identifies unofficial forms of heritage at a local level (Harrison 2013). Hence, any assessment or categorization of the assets conforming a historic urban area must consider both approaches and have a holistic view of the carriers of significance within a historic area.

Historic areas can be vulnerable to changes in weather patterns in a lot of ways (Sabbioni et al. 2008; Elena Sesana et al. 2021), not only direct “material” impacts on the built structure, but also other consequences that are very relevant for the cultural landscape, like changes on the population patterns, loss of intangible features, change in tourism and visitor numbers, and disruption of socio-economic activities, being the traditional ones especially vulnerable. The effects of climate change on cultural diversity and socio-cultural interactions; and impacts as the loss of the sense of community, traditional knowledge, cultural identity or natural and socio-economic systems have been already documented (Adger et al. 2013; Cassar et al. 2007; IPCC 2014a), but few studies have considered climate impacts on cultural heritage with a multidisciplinary approach (Alessandra Gandini, Garmendia, and San-Mateos 2017). Therefore, as the impacts of climate change on heritage conservation have a complex relationship among physical, social and cultural aspects, they all have to be considered when assessing threats derived from the change in climate conditions.

There is strong evidence that when people are displaced or their places of importance are damaged, their cultures and communities diminish or became endangered. The level of connection that members of a community have with the place or environment in which they live is called attachment to the place. This concept, well established in sociology, defines the identity that is created around a settlement, based on the pride of belonging to a place and the networks that are created in it. It is an important factor in the level of well-being and is used as an indicator to assess the sustainability of a community (Adger et al. 2013). Traditional and indigenous communities, in general, may be more vulnerable to climate change but are not passive in the face of environmental changes, since traditional resource management systems are responses to cultural, social and environmental change in the past. International discourse has recently begun to recognize traditional knowledge systems as essential tools for monitoring climate change on a local scale, and for successfully implementing adaptation strategies linked to sustainable development (Long and Smith 2010).

2.3.1 Conservation framework

Heritage can be a very difficult concept to define; it can be understood as a physical object that can be passed from one generation to the next, something that can be conserved or inherited or things that because of its historic or cultural value are worthy of being preserved. The more contemporary concept of heritage also incorporates various practices and intangible aspects such as language, culture, traditions or any cultural behaviour in a broader sense. According to Harrison (2010) (Harrison 2010), these *practices of heritage* are intangible customs and habits that form our collective social memory. Objects of heritage (tangible) alongside practices (intangible) shape our identity as communities. Within the contemporary theory of conservation, cultural heritage has evolved to a more broad and complex term since the Venice chapter (ICOMOS 1964), becoming this more inclusive and integrated interpretation of the concept. This intangible assets in heritage can manifest as a set of directs relationships with an object, building or place, but also as practices that seem to be separated from material elements. However, these practices cannot be separated from physical, tangible elements and places, as they are always entangled and related in different ways.

Heritage, therefore, can be defined as a set of attitudes and relationships with the past (Walsh 1992; Harrison 2013); and conservation as the choices we make about what to remember and what to forget, often in the light of a potential threat and in relation to future generations. The theory of contemporary conservation was born at the end of the 19th century as a defence against the destructiveness of capitalism after the industrial revolution. It was a manifestation of how a threat raises awareness about culture and the legacies of the past. David Throsby defines heritage as capital that produces a stream of benefits either economic or sociocultural, and it uses the term heritage asset to refer to communities' inheritance (Throsby 2012).

As stated by Harrison (Harrison 2013), we can talk of official and unofficial heritage; differentiating between the objects, buildings, or practices that are set apart from everyday and conserved motivated by some sort of official legislation or charter and the unofficial heritage that englobes the buildings objects or practices that have a significance for individuals or communities but are not recognised through legislative protection. As in any place, these two forms of heritage usually intertwine. This creates the dichotomy concerning who defines and has the right to the official definition (G. J. Ashworth, Graham, and Tunbridge 2007). This debate on the different conceptualization of heritage has currently many authors differentiating on heritage management paradigms or discourses (G. Ashworth 2011; Patiwael, Groote, and Vanclay 2019; L. Smith 2014; Harrison 2010; Pendlebury 2013) and the relationship between them has given rise to critical heritage studies as an interdisciplinary field of research.

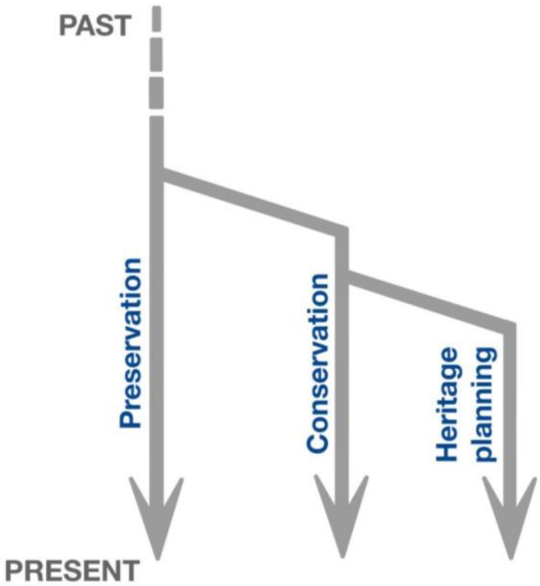


Figure 7. Visual representation of the three paradigms of heritage based on (G. Ashworth 2011).

As stated by Ashworth (2011) (G. Ashworth 2011), in the last few centuries, three different paradigms have converted into areas of study in the field of heritage, coexisting simultaneously instead of replacing each other, as it tends to happen with paradigm shifts. These paradigms tackle the relationship between preservation and development, or change [Figure 7]. The preservation paradigm contemplates development as an opposite, and has as a goal to maintain what exists now into the future unaltered or with the maximum mitigation possible of the effects of change. The idea of preserving objects that no longer have a function for their own sake, assigning value to specific moments in the past, even when there are out of context, is relatively recent. It arguably gained momentum in the industrial revolution, as a reaction to change. A lot of the legislation regarding heritage in western countries and especially in Europe, are based on preservation principles (G. Ashworth 2011). The conservation paradigm gained relevance in the 1960s, and can be considered an evolution of the preservation idea. It added function to form, shifting the focus from individual elements or buildings to ensembles. Conservation can be defined as preserving purposefully, considering contemporary use when assessing preservation. The heritage planning paradigm conceptualises heritage for the contemporary use for the current needs of the past that has been shape by history (G. J. Ashworth, Graham, and Tunbridge 2007). Therefore, this paradigm considers that the relevance of heritage is not about its intrinsic authenticity or historical value, but about the contemporary narrative attached to it and subjective to the value given to it in a particular time and context.

Furthermore, one of the challenges in the area is the definition of resilience within heritage management. As human societies have often led a process of co-evolution with nature, people and nature have evolved over time creating unique bio-cultural systems. The concept of resilience may therefore be approached as a holistic assessment of the relationship between communities and their environment and its evolution (Lombardini 2014). The ecological definition of resilience is considered the most complete one: “the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks and therefore identity” (Walker et al. 2006). In turn, the definition in physics and engineering is: “an intrinsic property of a system that allows it to switch from one equilibrium state to another without losing its basic internal structure, otherwise defined also in terms of the identity”(Berkes and Folke 2000). Both the ecological and the physical definitions use the concept of identity as the basic property to be maintained, while being able to adapt to an impact. The IPCC (IPCC 2014a; Eligible, Ineligible, and Count 1963) on the other hand, defines resilience in its glossary of terms as “the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions”. As seen in these definitions, resilience is based on facing change while maintaining identity. To tackle both of these concepts in the field of cultural heritage means that the approach will depend on a debate over the different conceptualizations of heritage, to which many authors are contributing by differentiating between the previously mentioned heritage management paradigms and discourses (G. Ashworth 2011; Patiwael, Groote, and Vanclay 2019; L. Smith 2014; Harrison 2010). Even though built heritage may be considered in terms of an adaptive system to its environment and climate, a holistic assessment of the resilience of cultural heritage will therefore require the concept of authenticity or “essential basic structures and functions” in the case of the IPPC definition. This approach will be based on the discourse or paradigm through which the heritage is addressed, and the barriers of irreversibility that climate change adaptation must undergo in an urban system (Turner and Singer 2014).

This dissertation will consider both a bottom-up and top-down approach when addressing assets cultural or heritage value. It considers the conservation paradigm as a basis, as the heritage regulations and protection regulations of the case studies are based on this premise. Nevertheless, a bottom down approach to cultural value will be added as a perspective, considering the relevance of assets to the sense of place and life within the historic area even if they are not “officially” categorized as heritage.

2.3.2 Potential impacts of HW in HUA

As stated in (Cassar et al. 2007) the impacts of climate change in heritage conservation have a complex relationship between physical, social and cultural impacts, and they all have to be considered when assessing threats by climate parameters. When adapting to a changing climate, certain ways of doing things may have to change. This fact puts cultural traditions in the first line of the climate change adaptation process (Ford and Smit 2004), and have to be assessed when considering, not only risk, but when measuring resilience.

Some references in bibliography stand out by being constantly quoted in publications on the subject (Elena Sesana et al. 2021). The main four references that can be highlighted are: a report for a scoping study of the likely risks and strategies for adaptation to climate change impacts in the English historic environment (Cassar 2005), the European Noah´s Ark Project and its final report “The atlas of climate change impact on European cultural heritage: scientific analysis and management strategies” (Sabbioni et al. 2010), the materials gathered for the course “Vulnerability of Cultural Heritage to Climate Change” and the workshop “Climate Change and Cultural Heritage” held in Ravello, Italy between the 14th and 16th of May 2009, (Sabbioni et al. 2008) and the European project “Climate for Culture” and its conclusion brochure “Built cultural heritage in times of climate change” (Leissner et al. 2015).

The first reference is a report by the UCL centre for sustainable heritage on the risks and strategies for adaptation to climate change impacts, focused on the English historic environment. It provides mapping on the possible future climate scenarios for the different regions and their risks (Cassar et al. 2007).While this report focuses on English heritage, it has the same approach as one of the most cited and referenced projects on the impact of CC in built heritage, which is the European project Noah´s Ark. The objective of Noah´s ark was to analyse the meteorological parameters linked to climate change that affect the heritage in Europe, focusing on the impact on materials and, therefore, on tangible built heritage. For this aim, the project joined European institutional and research partners for the elaboration of maps of climate risk and vulnerability; with the aim of developing them as tools for the heritage managers in the formulation of adaptation measures and strategies against the effects of the CC. Its final report was "The Atlas of the Impact of Climate Change on European Cultural Heritage: Scientific Analysis and Management Strategies" (Sabbioni et al. 2010) which brings together an overview of climate change in Europe and its impact on the built heritage, focusing on the different possible pathologies by material, and not on individual monuments. It is an extensive and comprehensive study focused on the development of “climate risk and vulnerability” maps for built heritage on a Europe-wide scale, taking advantage of the expertise of the different partners of the Project.

Contemporary to the end of the Noah´s Ark Project, the book titled “Climate Change and Cultural Heritage” (Lefèvre and Sabbioni 2010) was published, compiling the materials and conclusions of the course “Vulnerability of Cultural Heritage to Climate Change” and the workshop “Climate Change and Cultural Heritage”, held in Ravello and Strasbourg in 2009. This publication contains the texts used in the course, many of them outlining the results of Noah´s ark Project, mapping the effects of climate change in materials as well and providing directions on mitigation and adaptation. It also contains the very relevant “Recommendation on the vulnerability of cultural heritage to climate change”, initially proposed by the participant of the workshops, which then was approved by the Committee of Permanent Correspondents of the European and Mediterranean Major Hazards Agreement at its 57th meeting in 2009.

The other most referenced project on this subject to date has been Climate for Culture, European project within the H2020. The goal of Climate for Culture was to assess future projections of outdoor climate changes on the indoor environments of Historic Buildings in Europe and Egypt, using climate indices in building simulation tools. Along with many publications written by the partners of Climate for Culture during the duration of the project, the final brochure summarizes the main results and conclusions of the project as maps of future climate-induced risks for historic buildings and their interiors. The brochure includes a chapter in Risk assessment, focused on the different envelope materials and considering mechanical, chemical and biological deterioration mechanisms (Leissner et al. 2015).

With these four as the more cited references, there is a relevant body of research on climate change impact on heritage materials (Brimblecombe, Grossi, and Harris 2011; Zhou, Carmeliet, and Derome 2020; Huijbregts et al. 2012), that serves as the foundation for the future development of indicators. For the assessment of vulnerability, as we are analysing an urban area were tangible and intangible heritage layer and intersect, a mapping of the weathering and degradation of materials is essential.

2.4 Risk assessment methodologies

To make an introduction to risk assessment frameworks, it is important to address that most methodologies base their approach on the ISO 31000 (Leitch 2010). The process for risk assessment following the ISO 31000 [Figure 8] starts with the selection of potential risks, assessing them individually either qualitatively or quantitatively to evaluate their impact and shorting them depending on their severity (Creed et al. 2019; Tonmoy et al. 2018). This is a linear risk assessment approach that fails to address more complex kind of risks that cannot be measured by just addressing individual components, and needs an assessment of bigger systems, as it is the case of the effects of climate change (Cavallo and Ireland 2014).

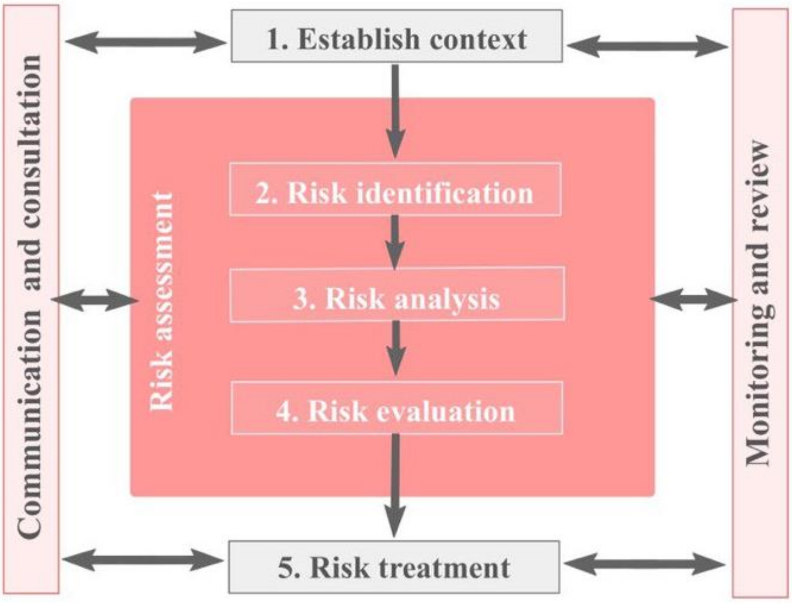


Figure 8. The process for risk assessment following the ISO 31000 (Leitch 2010) (adapted from (Scott et al. 2013)).

As mentioned before in this dissertation, cities, and especially historic urban areas, are a complex interaction of different systems and, consequently, it is hard to understand their vulnerabilities. The realisation of this complexity is causing a paradigm shift from single hazard and direct risks to more holistic approaches to climate change impacts and hazards, considering more complex risks (Simpson et al. 2021; Fraser et al. 2020) .Complex risks are intrinsic to an extremely anthropogenic environment such as historic areas. Hence, the analysis of risk must combine the natural and human factors that affect the magnitude of the risk, not only the hazard. In this context, in 2015, the United Nations member states adopted the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR 2015) which was designed to improve upon the previous Hyogo Framework for Action [Figure 9] (United Nations International Strategy for Disaster Reduction 2019) based on the ISO 310001. The natural and human factors are within the Exposure and Vulnerability of both approaches. Furthermore, the updated Sendai framework considers human and ecological systems, in contrast to the just economic vulnerability considered in the Hyogo (United Nations International Strategy for Disaster Reduction 2019).

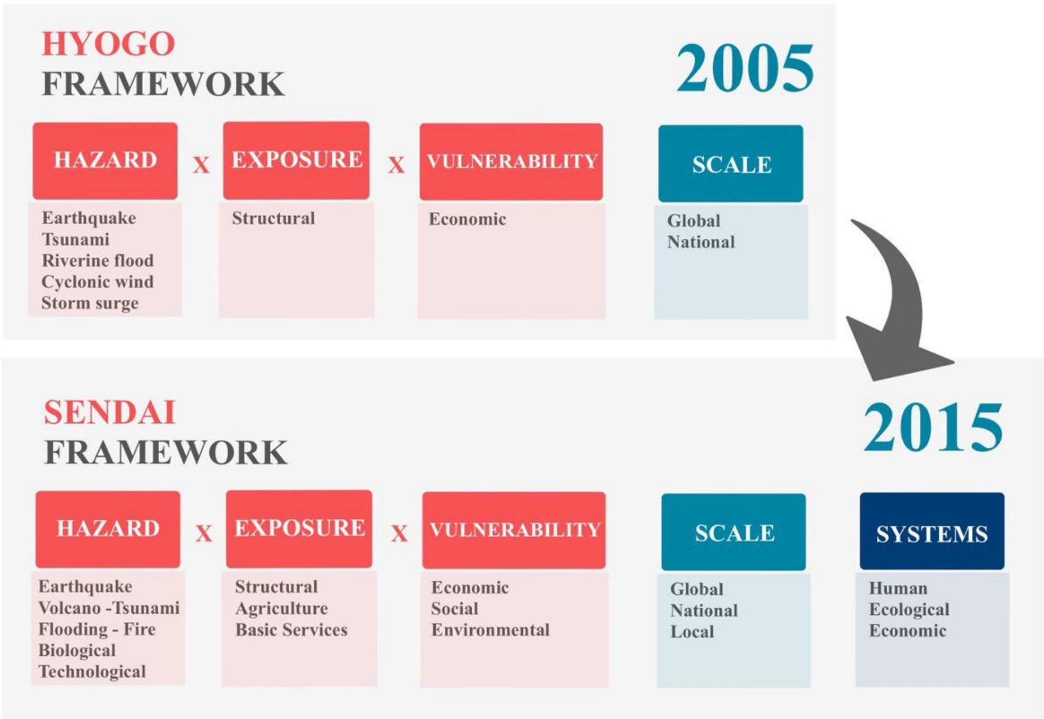


Figure 9. HYOGO and SENDAI frameworks from the UNISDR (adapted from The Global Assessment Report on Disaster Risk Reduction published in 2019 by the UNISDR (United Nations International Strategy for Disaster Reduction 2019)).

The Global Assessment Report on Disaster Risk Reduction published in 2019 by the UNISDR (United Nations International Strategy for Disaster Reduction 2019) also focuses on complex and systemic risks, addressing that to assess complex and interconnected systems, new views of risk are necessary and advocates for a more dynamic and three-dimensional view on risk. For this purpose, the report analyses and defines systemic risks addressing them in the context of urban areas and introduces a new Global Risk Assessment Framework (GRAF 2020) [Figure 10]. This new framework includes global hazards (not only climate change hazards) and related exposure and vulnerability. Regarding climate change risk assessment, the main particularity is that adds a variety of systems and scales to the approach, compared to the Sendai framework from 2015.

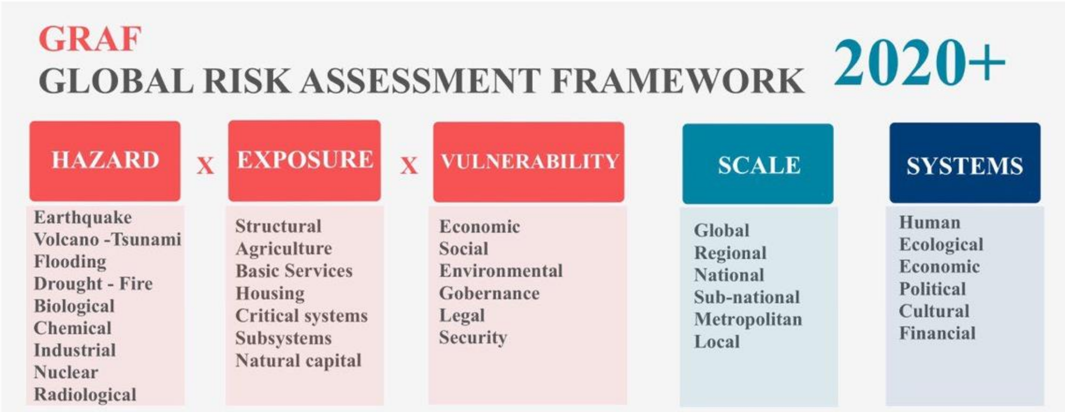


Figure 10. Global Risk Assessment Framework (GRAF 2020) (Adapted from The Global Assessment Report on Disaster Risk Reduction published in 2019 by the UNISDR (United Nations International Strategy for Disaster Reduction 2019)).

The SFDRR defines "the need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability and hazard" (UNISDR 2015). In this line, the Office of the United Nations Disaster Relief Coordinator (UNDRO) cites a definition from UNESCO for risk in its report meeting for Natural Disasters and Vulnerability Analysis, defining risk as "the probability of loss resulting from the product of hazard, vulnerability and value" (UNDRO 1980). This definition has been widely adopted and adapted by the institutions dealing with disaster risk, such as the United Nations Office for Disaster Risk Reduction (UNISDR) and the IPCC. The IPCC adapted this definition for climate change assessment, developing it in each subsequent report. In its Fifth Assessment Report (AR5) (IPCC 2014a), risk was defined as a "probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur"; risk was therefore characterized as the "result of the interaction between hazard, vulnerability (susceptibility to harm) and exposure" (IPCC 2014a). This definition has been updated in the Sixth Assessment report (AR6), just published in 2022, to "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change." (IPCC 2022). The components of risk have been updated to add that the risk is a result of the "dynamic interaction" of the climate hazards and the exposure and vulnerability of the systems under assessment (IPCC 2022). Therefore, in the last years, the recent frameworks and methodologies developed for risk assessment to climate change have addressed risk as the potential and diverse impacts on human or ecological systems, as well as on the physical system, recognizing the complexity of those latent impacts (Quesada-Ganuza et al. 2021; Alessandra Gandini et al. 2021; Reisinger et al. 2020).

This dissertation bases its risk assessment framework on the one set by the IPCC in its AR5 report, as was the most current one during the development of the research of this thesis. The AR6 assessment report was published on the last months of the development of this PhD dissertation and provides a different approach to risk assessment, with a more dynamic approach to the interaction between the drivers of risk. Nevertheless, the outcomes of this doctoral thesis will serve as basement for a future dynamic analysis.

The new AR6 framework for risk has an expanded consideration of the responses among the determinants of risk and makes emphasis on their interactions (IPCC 2022) [Figure 11]. This refreshed approach makes more explicit the specifics of the interactions among determinants of risk, as well as among multiple risks, providing the basis for more detailed and accurate risk assessment.

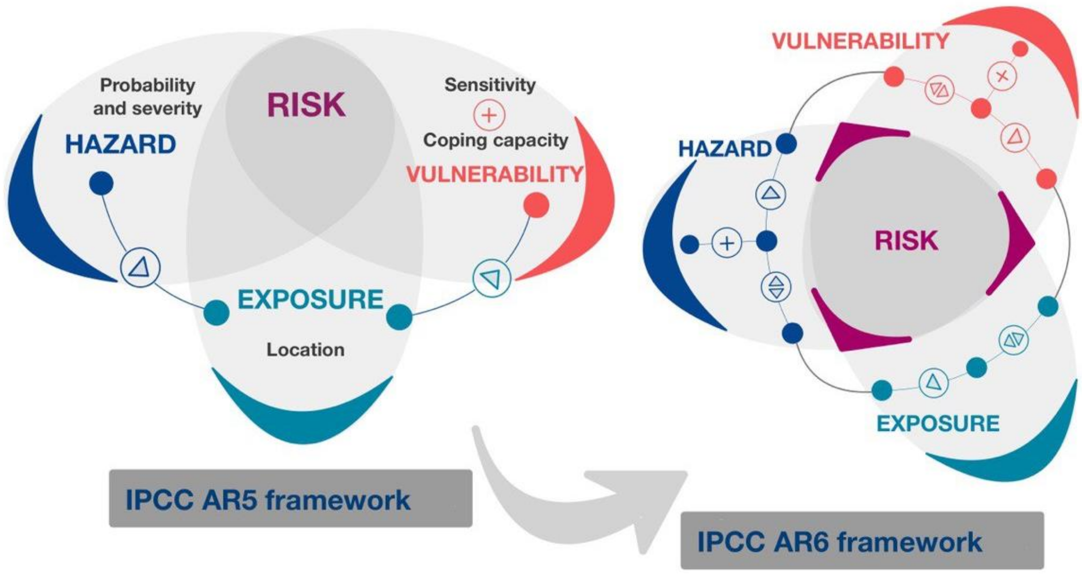


Figure 11. AR5 and AR6 IPCC framework (Adapted from the Fifth and Sixth Assessment reports (IPCC 2022; 2014a)).

Therefore, climate change risk assessment can present increasing complexity based on whether it considers only a single driver for each determinant of risk, multiple interacting drivers within determinants of risk, or even interacting risks. As mentioned, determinant refers to hazard, vulnerability, and exposure, within which the term driver refers to their individual components that interact to affect the overall nature of a risk. When addressing climate change impacts, risk results from dynamic interactions between climate-related hazards and the exposure and vulnerability of the affected system; but with climate change responses, risk results from the potential for such responses not achieving the intended objective(s), or from potential trade-offs or negative side-effects (IPCC 2022).

Hence, this thesis bases its framework on the following definitions and framework provided by the AR5 assessment report of the IPCC (IPCC 2014a).

To set the base for risk assessment, a brief conceptual background on the meaning and evolution of the determinants of risk, hazard, exposure and vulnerability are needed.

Following the IPCC approach, hazards derived from CC that impact urban areas are: extreme temperature events, cold and heat waves, wildfires derived from heat waves;

flooding events derived from extreme precipitation, storms and sea level rise; and climate change as a hole, the overall rise of temperature and consequential change in climate.

Exposure in this framework is defined as “the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected” (IPCC 2014a). Hence, it refers to the elements in the area affected by the hazard, it is possible for an asset to be exposed but not be vulnerable; yet, to be vulnerable it needs to be exposed to the event.

The concept of vulnerability within the framework of AR5 is key to the characterization of risk, and its assessment implies characteristics and processes that are evaluated in different ways, depending on the discipline (Brooks 2003; Adger 2006). Hence, following the AR5 definition, vulnerability is the propensity or predisposition of an element exposed to extreme events (i.e. climate change events) to be adversely affected, and this vulnerability combined with hazard and exposure will determine the risk. The IPCC definition of vulnerability involves sensitivity to the hazard and its lack of capacity to cope with the adverse effects of climate change (IPCC 2014a). While sensitivity is a relatively straightforward concept, coping capacity is understood in a different way, depending on the system that is under assessment. In the AR5, coping capacity is defined as “the ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term”. An anthropocentric approach to the coping capacity of an urban system assesses inequalities in opportunities and resources, and the awareness of the people forming part of the system towards risks. In the case of a hazard-oriented vision, the evaluation of the natural event is emphasized, neglecting the capability of people and communities to overcome its negative effects. Both approaches involve limitations with regard to their understanding of the relationships between urban elements and their inhabitants. As a result, in the case of assessing the coping capacity of an urban system, the approach has to take into consideration the different layers and dimensions that conform it.

2.5 Risk assessment on historic urban areas

The concept of vulnerability is key to the characterization of impacts, and its assessment implies characteristics and processes that are evaluated differently, depending on the discipline (Brooks 2003; Adger et al. 2013; Adger 2006). As seen in the previous section, IPCC’s definition of vulnerability involves sensitivity to the hazard and its lack of capacity to cope with adverse effects (in this case climate change) (IPCC 2014a). While sensitivity is a relatively straightforward concept, adaptive capacity is understood in a different way depending on the system that is being assessed. For example, while natural risk approaches refer to vulnerability primarily as proximity to hazards, in the field of public health vulnerability is related to socio-cultural, economic and political characteristics. An anthropocentric approach to the adaptive capacity of an urban system assesses inequalities in opportunities and resources, and the awareness that the people, who are part of the system, have about risks (starting point of vulnerability). In the case of a hazard-oriented vision, the evaluation of the natural event is emphasized, neglecting the ability of people and communities to overcome negative effects. Both have limitations to understand the relationships between urban elements and their inhabitants, and none contemplates the relationship of the changes that this adaptation implies on heritage, as seen in resilience conceptualization.

Indicators for sensitivity and adaptation capacity are of great importance in risk assessment, and to determine the solidity of future strategies and policies. However, the characterization of adaptive capacity, as mentioned with resilience, proposes a challenge and needs to be addressed when developing any methodology for risk assessment that involves cultural heritage. The characterization of vulnerability in the field of cultural heritage is a noticeable gap in knowledge; and it needs to be approached taking into consideration the different heritage management discourses.

As a specific holistic approach (considering intangible and tangible heritage) of risk assessment regarding climate change impact in cultural heritage is missing from literature, the current state of the art on the subject can be divided into two lines. The first one, impact assessment in heritage sites; the second one, climate change risk assessment in urban areas.

2.5.1 Heritage impact assessment

The first international letter that considered a specific type of emergency that endangered the conservation of cultural heritage was the UNESCO Convention in The Hague in 1954, with the Blue Shield initiative. This convention focused on the risk of armed conflict, and highlighted the importance of protection mechanisms such as documentation and registration. Therefore, fire and security were the first references to risk to cultural heritage. During the 1990s these plans were reviewed and consolidated, the UNDRR declared in the 1990s the International Decade for Natural Disaster Reduction; and the war in Yugoslavia meant the revision of the Hague convention. During this time, ICCROM and UNESCO had a series of workshops and panels to analyse these scenarios; and within this context, Herb Stovel developed the document Risk Preparedness Guidelines for World Cultural Heritage Sites, 1998, where he studied the relationship between disaster, conflict and weathering on cultural heritage. This book, published by UNESCO, ICOMOS, and ICCROM in 1998, stated definitions for risk and related concepts. Focusing on managers and decision-makers, it provided guidelines specific for heritage sites; being its goal to involve cultural heritage in risk-preparedness plans. Risk assessment for prevented conservation was first used in the early 2000s on museum collections and it was then merged with the problems faced by heritage sites. During this time, the concept of risk for cultural heritage expanded from natural disasters and armed conflict, to climate change and sustainability.

In this context, ICOMOS published in 2011 the HIA guidelines (Guidance on Heritage Impact Assessment for Cultural World Heritage Properties), as an attempt to evaluate the impact of new planned developments (as new infrastructures or high buildings) on the Outstanding Universal Value (OUV) of World Heritage Sites (WHS) (ICOMOS 2011). This document was developed as a tool to assist WHS on threats to heritage values, after the delisting of Dresden due to the negative impact of a planned development; and it has been firmly stablished in the management of WHS. It is important to address the implicit assumptions of the HIA guidelines, which are based on a preservation discourse, mainly on the way they address impact and change (Patiwael, Groote, and Vanclay 2019), and how they are completely focused on OUV, which has itself been questioned as a concept within ICOMOS (Araoz 2008).

Beside the approach of UNESCO, ICOMOS and the different organisations, there is a very relevant body of research on impact and risk assessment on historic areas focused on the buildings or archaeological sites (Daly 2014), with the more frequently assessed hazards being floods and earthquakes. Earthquakes is a repeated and classic concern in Heritage management (Despotaki et al. 2018), especially since the occurrence of subsequent earthquakes during the late 70s and early 80s, like the ones in Guatemala or Italy, causing a rise in awareness for natural hazards in the heritage management community- This resulted in the publication of “Between Two Earthquakes” in 1987 by Sir Bernard Feilden, then director of ICCROM. In this publication, the term risk is clearly defined for the first time and it states and organises the measures to be taken before, during and after an earthquake (Feilden 1987).

Since floodings, caused either by torrential rains or the rise of sea level, are one of the most pressing hazards caused by climate change (A Gandini, Prieto, et al. 2018), this line of research is one of the most active, gathering a lot of interest for the development of methodologies for risk assessment of built cultural heritage (A Gandini, Prieto, et al. 2018; Stephenson and D’Ayala 2014; Miranda and Ferreira 2019; Quesada-Ganuza et al. 2021). These methodologies, together with others that take a multi-hazard approach or the assessment of specific historic areas (Romão, Paupério, and Pereira 2016; Forino, MacKee, and von Meding 2016; Matheos Santamouris, Cartalis, and Synnefa 2015) tend to focus on the risk for buildings and tangible assets during the emergency phase of the hazards, the catastrophic events and the identification of the vulnerability of the assets (Quesada-Ganuza et al. 2021).

In the last decade, a growing interest and focus in climate change has been evident in the reports and work plans of heritage organs such as ICOMOS, with its climate change working group (Markham et al. 2016); and UNESCO, that has developed several reports (Cassar et al. 2007) and policy documents addressing the impacts of climate change in the World Heritage Sites (UNESCO 2008). Besides the efforts undertaken at international level, the European Union is also contributing to the topic by including cultural heritage risk assessment and prevention in the agenda, with the EU Work plan for Culture 2019-2022 including a topic on adaptation to climate change (Council of Europe 2018), and several recommendations (CM/Rec(2018)3) (Bonazza et al. 2018). When developing strategies to protect cultural heritage and urban areas from any environmental hazards, risk assessment is an essential step. While the impacts of current and future climate change on natural systems, socio-economic systems, and urban systems have, in general, been well documented (IPCC 2014a), there has been little research on climate impacts on cultural heritage and historic areas. Hence, despite the high level of interest in climate change impacts on heritage and the abundance of literature addressing the need for research in this area (Brabec and Chilton 2015), assessment methodologies for understanding the impacts of climate change on cultural heritage and historic areas through a holistic approach represent a noticeable gap in the knowledge.

Within this context and the complex systems of urban areas, the special significance of historic urban areas is due to their specific characteristics and importance, both from the perspective of their vulnerability and their resilience (Longworth 2014; Brabec and Chilton 2015; Fatiguso et al. 2017). Hence, there is a need for specific approaches towards assessing the risk that climate change presents to their conservation.

2.5.2 Climate change risk assessment for urban areas

The field of climate change risk assessment for urban areas has been gaining a lot of interest in the last years and is emerging as a priority when developing policies to reduce the impact of extreme events on the built environment. Currently, more than 50% of the world's population resides in urban areas, with an estimated increase to 60% by 2050 (UNISDR 2017). This fact, together with the spatial and physical characteristics of cities, the vulnerability of the population and the critical nature of environmental challenges are particularities that determine risk assessment and adaptation strategies to climate change in urban areas. The greater population density, the larger concentration of productive activities, urban planning, etc. are some of the factors and characteristics that differentiate the vulnerability of urban areas causing urban specific phenomenon, and can amplify the negative consequences of different climatic events. UHI (Urban Heat Islands) or greater risk of flooding due to the lack of permeable soil are intrinsic to urban areas and demand particular methodologies for the risk assessment (Gartland 2010; Romero-Lankao et al. 2016).

The concepts of vulnerability and resilience, linked to sustainability, within the urban system are currently often discussed in literature (Romero Lankao and Qin 2011; Gencer et al. 2018; Meerow, Newell, and Stults 2016). These definitions are not resolved issues, but they imply shifting concepts which relevance will continue to increase, as the impacts of the change in climate in cities is getting worse and the need for more robust and sustainable urban environments are becoming even more pressing.

The vulnerability of urban environments is frequently linked in the literature to their socio-economic and physical conditions, such as geographical position, materials, urban plot and morphology, wealth and governance system etc. (EEA 2017). These characteristics will determine the severity of the resulting impacts when considering specific climatic events and the effect of changes in climate. As a result, the vulnerability of urban environments is a fundamental characteristic to study when considering the relationship of urban systems with the environment and climate (Georgi et al. 2012). As previously stated, vulnerability can be defined as the sensitivity and lack of adaptive capacity of a system (IPCC 2022). A relevant line in the literature discusses the conceptualization of the response capacity dividing it into the planning and preparation in advance of climate hazards and the ability to cope with or recover from the climate hazards as they happen (Mccarthy et al. 2001; Georgi et al. 2012). These differences in adapting capacity are a very relevant concept when integrating the layers of Cultural Heritage into the assessment of urban areas, as their main difference is the time scope. Coping capacity refers to the current ability to respond to the short-term effects of an extreme climate-related event, while adaptive capacity refers to the longer-term capacity to plan for preventing and/or managing the potential impacts of climate change (Eligible, Ineligible, and Count 1963). These definitions will have to be considered from the perspective of the different heritage discourses when analysing change in cultural heritage, as it was previously mentioned with the concept of resilience.

With the goal of increasing resilience to climate change and sustainability of urban environments, many methodologies for risk assessment to climate change, as well as resilience monitoring methodologies for urban areas have been developed in the literature. This methodologies usually focus on a specific threat like heat waves (Apreda, D´Ambrosio, and Di Martino 2019), earthquakes (Lucia et al. 2012), floods (Cirella, Iyalomhe, and Russo 2016) or multi-hazard scenarios (Borg et al. 2014; Georgi et al. 2012), but further research that considers the layers of cultural heritage and singularities of historic urban areas is missing from literature (Quesada-Ganuza et al. 2021). The state of the art on the Key Performance Indicators (KPIs) for these methodologies is a very relevant base to which the layer of cultural heritage could be added; developing new sets of indicators tailored to the particularities of cultural heritage as an asset to communities (when assessing any urban area) and the characteristics of historic urban areas.

2.6 Multi-criteria decision making methodology - MIVES

When it comes to decision-making and the prioritization of solutions, several multi-criteria methodologies have been developed over the last decades (Kabir, Sadiq, and Tesfamariam 2014), systematic framework that is able to reflect the multidimensional nature of the reality. In a multi-criteria method, the problem is disassembled into its component parts in order to analyse each one (Pujadas et al. 2017).

MIVES is a multi-criteria methodology developed for the assessment of sustainability in construction (San-José Lombera and Cuadrado Rojo 2010; San-José Lombera and Garrucho Aprea 2010; Aguado et al. 2012; Pons and Aguado 2012). Jointly developed by the Polytechnic University of Catalonia (UPC), Tecnalia and the University of the Basque Country (UPV/EHU), it combines Multi-Criteria Decision-making Theory and the value function concept and assigns weights using the analytic hierarchy process (AHP) (San-

José Lombera and Garrucho Aprea 2010). MIVES is used to give homogeneity to different types of variables measured with different units. It considers and relatively compares both quantitative and qualitative variables by transforming them to a comparable unit. Therefore, it provides a framework in which environmental, social, economic, and technical indicators can be taken into consideration and compared integrating them into a single index. This methodology is included within the multi-attribute utility theory since to obtain the value index of each alternative, a weighted sum is made of the valuations of the different criteria considered, assuming that there is certainty. That is, the preferences of the decision maker regarding the proposed indicators are known in advance.

For the assessment of a risk using the MIVES methodology, the different risk components are structured within a multi-criteria analysis framework according to pre-established criteria. This means that the approach of the entire valuation model is prior to the creation of alternatives. In this way, decisions are made at the beginning, when define the requirements that will be taken into account and how they will be assessed. The advantage of this approach is that decision-making is carried out without the influence of the evaluations of the alternatives avoiding the production of any type of subjectivity (Viñolas Prat et al. 2009).

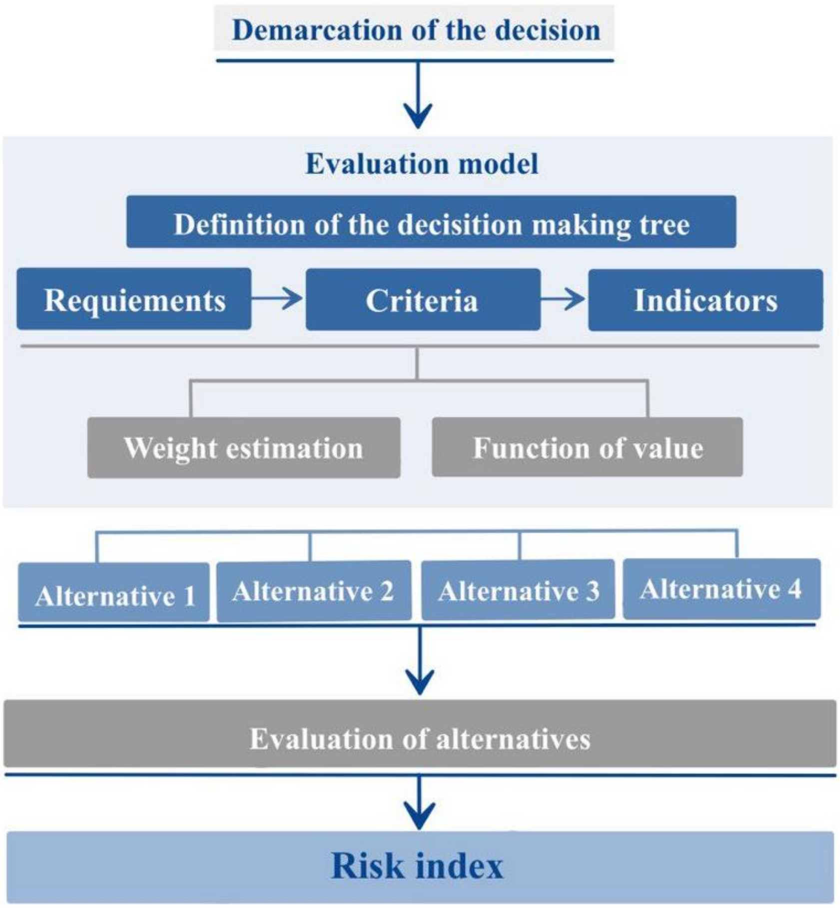


Figure 12. The algorithm in the MIVES methodology.

The MIVES approach has originally been used for the evaluation of alternatives in the building area. Figure 12 summarizes the base algorithm of the methodology. In it, initially the decision (to be taken) is defined, in this stage identifies and defines the problem to be solved, for example sustainability of a building technique, risk assessment, building a road, etc. Then, the tree is defined and requirements developed, choosing the criteria (sub-criteria) and indicators according to the type and conditions of the project. Next, the possible solutions that will solve the proposed problem are defined (alternatives); the number of alternatives will depend on the nature of the problem. It is of great importance to point out that, unlike other tools that assess or prioritize alternatives (for example AHP), the assignment of these alternatives can be developed before or after the definition of the model (requirements tree), which is a differentiating factor with respect to other evaluation approaches.

Finally, with the requirements, criteria and indicators and their weights already defined, the values are obtained of each of these in each alternative, to carry out the evaluation of each alternative and make the best decision. The assessment is carried out at three levels: indicators, criteria and requirements.

The phases of the MIVES methodology are (Viñolas Prat et al. 2009):

1. Demarcation of the decision: the person who makes the decision is defined. Once identified the objective of the analysis, the limits of the system and the boundary conditions are established.
2. Introduction of the decision-making tree: the aspects that will be taken into account in the decision-making process are determined.
3. Creation of value functions: some mathematical functions that allow the transformation of quantitative and qualitative aspects belonging to the last branch of the requirements tree are created in order to obtain ratings from 0 to 1.
4. Assignment of weights: the relative importance of each one of the indicator/criteria/requirement in relation to the rest belonging to the same branch. Consistency is checked.
5. Assessment of the alternatives: the value index is obtained for each of the alternatives.
6. Carrying out a sensitivity analysis: the possible change in the value index is analysed for each of the alternatives If the weight or value function are changed in the early stages, the possible variation in the value index is assessed. This is an optional phase within the methodology.

Demarcation of the decision

In this stage, the decision-making to be carried out is structured and delimited. For this, the problem is clearly defined, the person making the decision is identified and the limits of the system are stablished. The aspects fundamental to this are:

- **Defining the problem.**
- **Person making the decision.** Different agents can intervene in a decision with different points of view. In many cases, there is no alternative that is the best in each of the aspects considered. Therefore, obtaining the best alternative is not immediate and it depends on who makes the decision, responding to their clearly defined interests.
- **Systems limits.** To identify the decision making, is structured around three axes as can be seen in Figure 13. The limits of the system are represented by the lines that limit the different cubes with a lighter color. These cubes are the ones that will be studied during the decision making. In one of the axes, decision making breaks down throughout its life cycle, understanding by this the temporal phases of the different alternatives. In another axis, decision making is divided into all its components, that is, into the parts that make up the different alternatives. Finally, in the last axis are all those requirements in which to assess the different alternatives. Breaking down or structuring decision making into three axes helps to define very precisely what the decision-making is. In this way, the risk of forgetting requirements, components or stages of the life cycle decreases considerably and valuations of comparable and homogeneous alternatives are obtained.
- **What boundary conditions exist?** The circumstances surrounding the decision-making may be different depending on several factors: temporary, geographical, climatological, etc. To have comparable evaluation of the alternatives that solve a problem, the boundary conditions must be equal. Some of these boundary conditions can become determining factors of the pass or fail type. That is, in a shot of decision may appear determining factors of the economic type, time, etc. in which the alternatives must not exceed certain limits. The complete list of pass or fail conditions is called the checklist, that is, a list of minimum conditions that those alternatives that want to be valued must meet. In the event that the quantification of any of the conditions is below or above the predetermined limits, the alternative will not be considered.

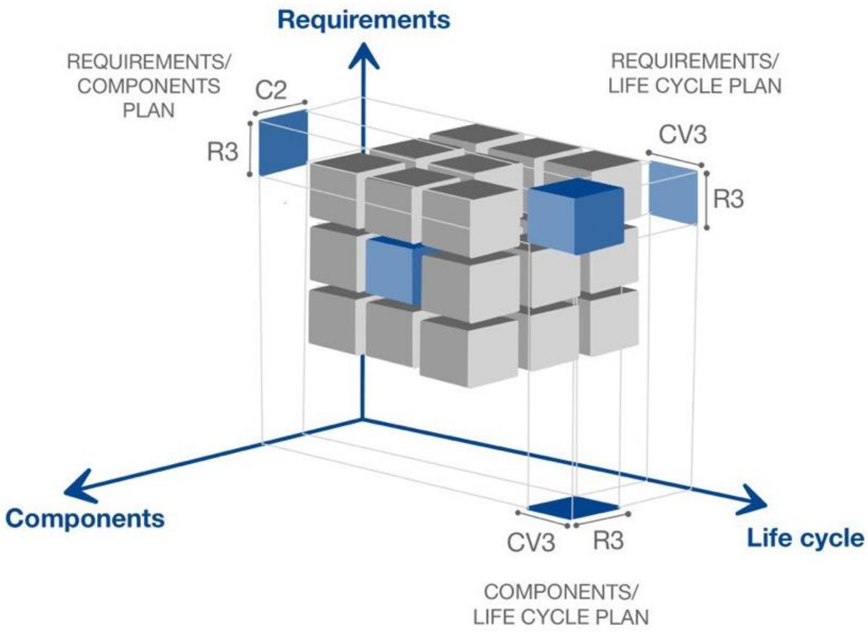


Figure 13. Decisition making axes in MIVES (based on (Villegas Flores, Aguado, and Universitat Politècnica de Catalunya. Departament d'Enginyeria de la Construcció. 2009)).

Decision-support tree

The decision-support tree is the branched order of the requirements, criteria and indicators that will be studied and that have been structured in the first phase. Figure 14 generically shows an example of a decision tree composed of branches. There are several levels in each branch, while each branch can be also divided into sublevels. In the first level, the most qualitative and general aspects called requirements are found.

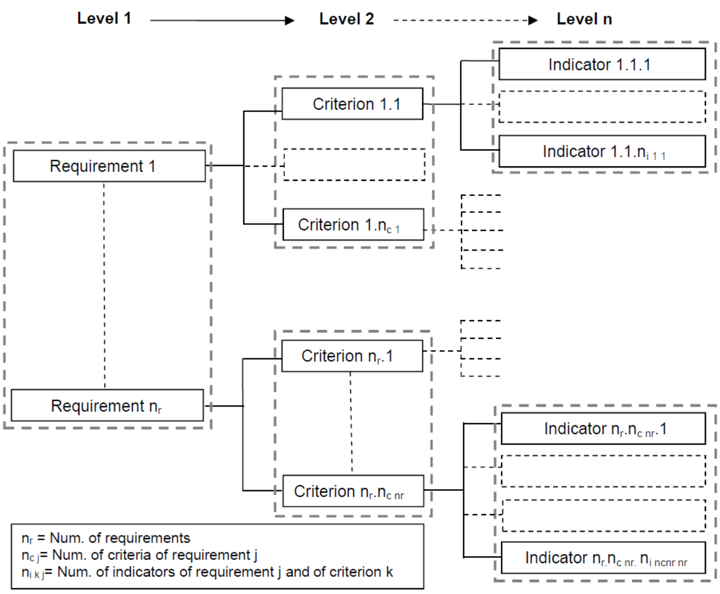


Figure 14. Generic decision tree used in MIVES (source (Viñolas Prat et al. 2009)).

At the intermediate levels of the branch are the criteria and sub-criteria, and at the last levels of the branch are the more specific aspects of the criteria that are going to be evaluated: the indicators. It is not advisable to make more than 3 or 4 branches or to exceed the number of indicators of 20, since the evaluations of the least important indicators can dilute the results of the really important indicators (Villegas Flores, Aguado, and Universitat Politècnica de Catalunya. Departament d'Enginyeria de la Construcció. 2009).

The requirements, criteria and indicators must faithfully represent what the person making the decision really wants to assess. Figure 15 represents a puzzle which pieces are the indicators. The complete rectangle constitutes the scope of decision making, the continuous and dashed lines subdivide the different requirements and criteria respectively. To obtain a correct decision-making tree, the ideal situation would be to fill the entire decision-making field with the different pieces of the puzzle. For this aim, these pieces must occupy the whole decision-making areas of the different criteria and requirements without overlapping or occupying areas that do not belong to them.

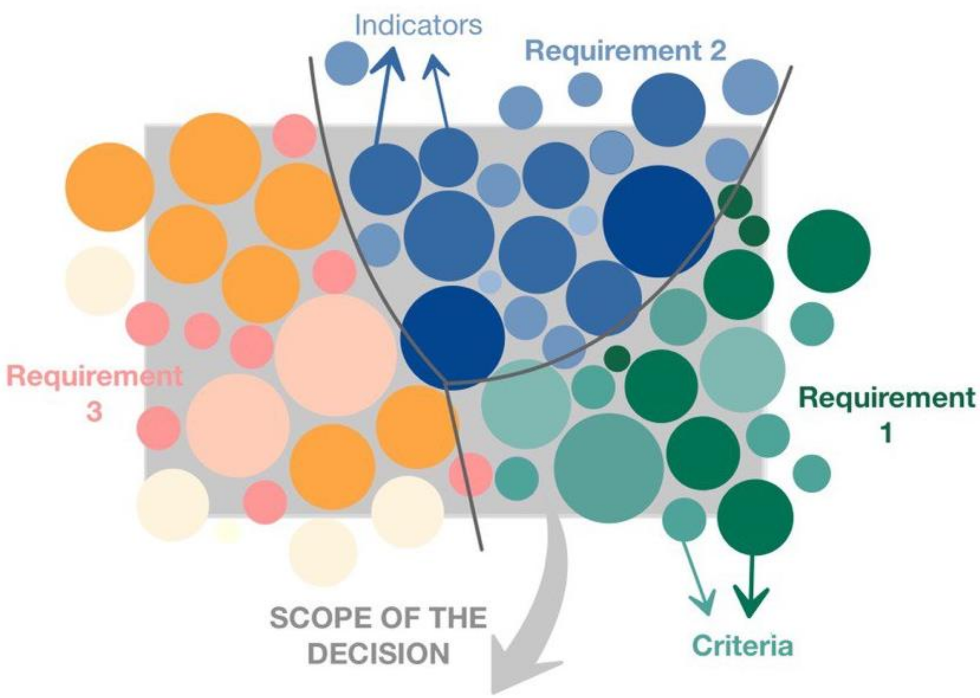


Figure 15. Representation of the decision making process in MIVES (based on (Viñolas Prat et al. 2009)).

The indicators chosen in the decision-making tree must be: representative, discriminant, complementary, relative, quantifiable, precise and traceable (San-José Lombera and Garrucho Aprea 2010).

Value functions definition

Value functions have the goal of making possible to compare the evaluation of the indicators which use different units of measurement. For example, they must be able to compare the following variables: time, cost, temperature, indicators quantified by attributes, etc. As the value function allows you to go from a quantification of a variable or attribute to a dimensionless variable between 0 and 1, it will be possible to make a weighted sum of the different evaluation of each one of the indicators. For the evaluation phase of the indicators, a value function is proposed for each one. This value function, which varies between 0 and 1 on the ordinate axis, represents status of null valuation or maximum valuation (saturation), respectively, for each indicators. On the abscissa axis is the indicator variable, which, in the case of being an attribute, can be converted into a variable using a score table.

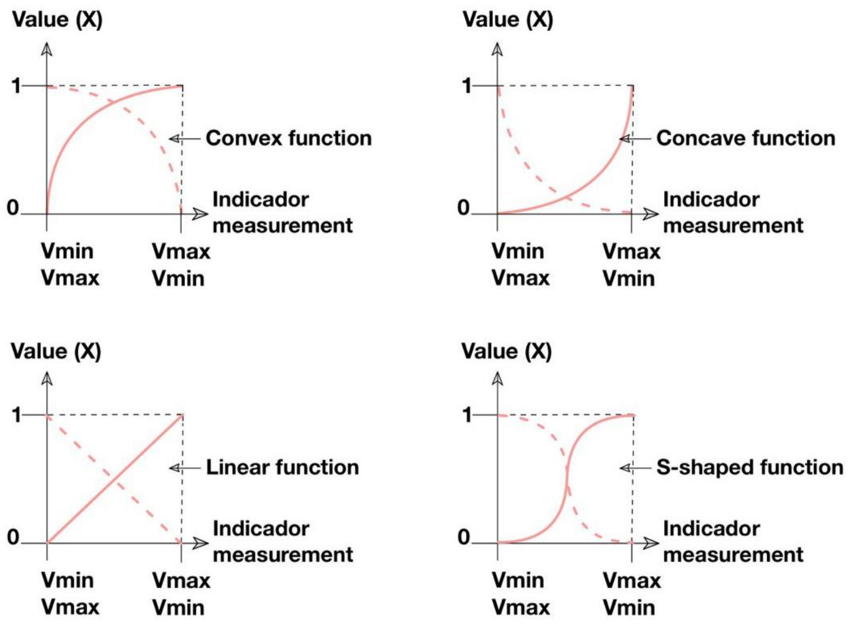


Figure 16. Different value functions (adapted from (San-José Lombera and Cuadrado Rojo 2010)).

The value function is defined by five parameters that, by varying them, allow to obtain all kind of shapes: S-shaped, concave, convex, or linear (Figure 16). The parameters that define the type of function are: K_i , C_i , X_{max}. , X_{min}. and P_i (Equation 1 for increasing functions). The value of B is calculated starting from the five previous values (Equation 2).

$$\boldsymbol{V_{ind} = B \times \left[1 - e^{-K \times \left(\frac{|X - S_{min}|}{C}\right)}\right]}$$

Equation 1. That defines the different value functions of each indicator.

Where: X_{min} is the value on the abscissa, whose valuation is equal to zero (in the case of increasing value functions).

X is the abscissa of the evaluated indicator (variable for each alternative).

P_i is a shape factor that defines whether the curve is concave, convex, straight, or "S" shaped. Obtaining concave curves for values of $P_i < 1$, convex or in the form of "S" if

P_i>1 and tending to straight lines for values P_i=1. It also determines approximately the slope of the curve at the point of inflection of coordinates (C_i, K_i).

C_i approaches the abscissa of the inflection point.

K_i approaches the ordinate of the inflection point.

B is the factor that allows the function to remain in the value range from 0 to 1. This factor is defined by equation 2:

$$B = \frac{1}{\left[1 - e^{-K\times\left(\frac{|S_{max}-S_{min}|}{C}\right)^{P}}\right]}$$

Equation 2. Value of B.

where X_{max} is the abscissa of the indicator that generates a value equal to 1 (in the case of increasing value functions).

Weight assignment

The assignment of weights is carried out within the same branch, that is, homogeneous aspects are compared. Thus, the weight of the indicators are calculated in relation to others belonging to the same criterion. The same is done with the criteria; the relative weight of the criterion within the same requirement is determined. All these requirement, criteria and indicators considered homogeneous are framed in Figure 14 (decision-making tree).

The weight of the requirements, criteria and indicators can be determined both by means of a direct score (in the case of few component elements of the group of comparison) and through the AHP methodology (Analytical Hierarchy Process – Process Analytical Hierarchy) (Saaty 1980).

AHP is based on a pairwise comparison of all elements with each other. This comparison is made according to a scale proposed by Saaty (Saaty 1980), in which intermediate situations and inverses are admitted:

1. Equal importance
2. Slightly more important or preferred
3. Most important or preferred
4. Much more important or preferred
5. Absolutely or extremely more preferred.

This gives rise to a comparison matrix like the one in Equation 3 for each block of comparison whose characteristics are:

1. Diagonal matrix with value 1 throughout the diagonal as a consequence of the fact that an element is compared to itself..

2. The inverse element of the array is the inverse number. For example, if the indicator *i* with respect to the indicator *j* has an importance of 4, when the indicator *j* is compared with the indicator *i*, the value will be 1/4.

$$A = \begin{vmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} = \dfrac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} = \dfrac{1}{a_{1n}} & a_{n2} = \dfrac{1}{a_{2n}} & \dots & 1 \end{vmatrix}$$

Equation 3. Pair-wise comparison matrix.

The eigenvector of a comparison matrix defines the weight of the corresponding requirement, criterion or indicator (value of w in Equation 4). In fact, the value of the eigenvector is approximately the mean of the n weights of the same requirement/criteria/indicator branch obtained from the comparison of the relative importance of all the same requirement/criteria/indicator with one of them taken as a reference. Since there are *n* reference elements (the *n* aspects), *n* weights for each of the aspects can be obtained.

$$A\,w = \lambda_{max}\,W[Id]$$

Equation 4.

On the other hand, the consistency (or not) of the comparison matrix must be calculated. To illustrate it, consider that “A” is twice as important as “B” and “B” twice as important as “C”, from which it follows that “A” must be four times as important as “C”. If the comparison between “A” and “C” is far from 4, it means that the judgment is not consistent. The maximum eigenvalue (λ max. of Equation 4) of the comparison matrix is a measure of the consistency of all judgments made. The calculation of the consistency of the judgments is a function of the computation of the eigenvalue. The maximum eigenvalue of the comparison matrix is equal to *n* in the case that the matrix is totally consistent. This eigenvalue increases if the inconsistency increases (Viñolas Prat et al. 2009). Thus, the higher the eigenvalue, the greater the inconsistency of the judgments made.

To calculate the consistency or not of the comparison matrix, the concept of the Consistency Index (C.I.) and the Random Consistency Index (R.I.) must be presented. The C.I. is defined by Equation 5:

$$C.I. = \frac{\lambda_{max} - n}{n - 1} < 0{,}1$$

Equation 5. Consistency index.

where, λ 1max. is the maximum eigenvalue.

The R.I. is the mean of all the C.I. of a randomly generated comparison matrix. It only depends on the size of the array and takes the values found in Table 3. Random Consistency Index (R.I.) values:

n	1	2	3	4	5	6	7	8	9	10	11	12
R.I.	0	0	0.525	0.882	1.115	1.252	1.341	1.404	1.452	1.484	1.513	1.535

Table 3. Random Consistency Index (R.I.) values.

The consistency ratio (C.R.) is the ratio between C.I. of the matrix and the mean of the consistencies of all possible comparison matrices of order *n* x *n* (Equation 6).

The value of C.I. depends on the eigenvalue of the comparison matrix and the value of R.I. appears in Table 3. Random Consistency Index (R.I.) values, which depends on the size of the matrix, that is, on *n*. In a consistent comparison matrix, the value of C.R. must not exceed 0.1:

$$C.R. = \frac{C.I.}{R.I.} < 0{,}1$$

Equation 6.

Evaluation of alternatives

Once the decision to be made has been adopted, the decision-making tree has been created with all the value functions and the weights have been assigned, the next step is to define the possible alternatives that can be presented for subsequent evaluation. In some studies, the alternatives have already been defined initially and therefore this should not be carried out.

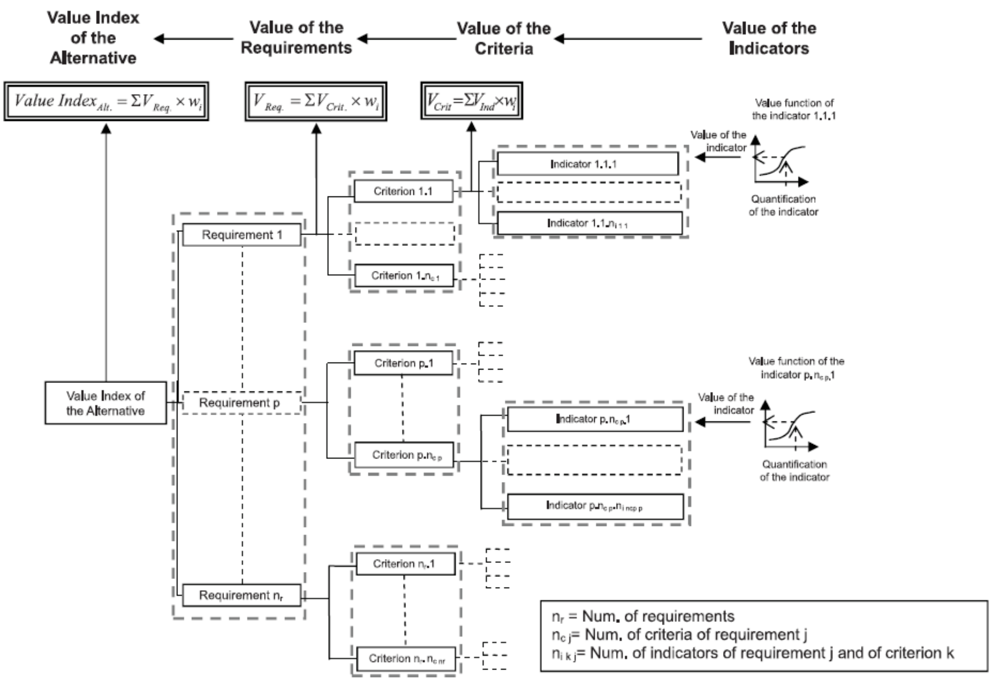


Figure 17. Evaluation of alternatives in MIVES (taken from (Viñolas Prat et al. 2009)).

The evaluation of alternatives is performed at three levels: indicators, criteria and requirements shown in Figure 17.

To obtain the assessment of the alternatives, the indicators, criteria and requirements must first be assessed. The indicators are the only aspects that are valued directly. The way in which the assessment of indicators, criteria and requirements is carried out is shown graphically in Figure 17 and is explained below:

Assessment of indicators: the assessment of the indicators is obtained from the value function and the quantification of each alternative in the studied indicator. The quantification of the alternative is the abscissa of the point of the value function, which ordinate is the valuation of the indicator for that alternative.

Evaluation of criteria: as shown in Figure 17 and in Equation 7, the criteria valuation is obtained from the valuations of the indicators belonging to the same criterion multiplied by their weights.

$$V_{criterion} = \sum_{i=1}^{n} V_{indicator_i} \times W_i$$

Equation 7. Criterion value.

where n is the number of indicators belonging to the same criterion.

Assessment of requirements: the requirements are assessed in a similar way to what was explained for the assessment of criteria (Figure 17 and Equation 8). The assessment of the requirements is the sum of the assessments of the criteria belonging to the same requirement multiplied by their weights.

$$V_{requirement} = \sum_{i=1}^{n} V_{criterion_i} \times W_i$$

Equation 8. Requirement value.

where n is the number of criteria hanging on the requirement under evaluation.

Value index of the alternatives: the valuation of the alternatives is obtained by adding the valuations of the requirements multiplied by their weights (Figure 17 and Equation 9).

$$Value\ Index_{alternative} = \sum_{i=1}^{n} V_{requirement_i} \times W_i$$

Equation 9. Value index of alternatives.

Sensitivity analysis

The sensitivity analysis is used to understand the influence of the different parameters on the value index obtained for each alternative using weight variations at the requirement level (Viñolas, Aguado, and Josa 2011).

When the preferences of the assessment may vary, a sensitivity analysis can be interesting in order to verify whether the final result of the alternatives presents important changes. This step, even if it is not mandatory, is recommended when several points of view are gathered together.

Variations within a maximum range of 30% are recommended for each requirement weight, as it has been demonstrated that differences of opinion usually stay within this range. The new value index is calculated according to:

$$V(A_i) = \sum_{j=1}^{n} w_j z_{ij}$$

Equation 10.

$$V'(A_i) = \sum_{j=1}^{n} w'_j z_{ij}$$

Equation 11.

where: w_j is the weight of requirement j

z_{ij} is the value of requirement j for alternative i

w'_j is the new requirement weight

$$w'_j = w\left(1 - \frac{\Delta\, weight\ of\ reference\ requirement}{100 - weight\ of\ reference\ requirement}\right)$$

Equation 12.

As a result, the decision-maker will obtain a ranking of solutions based on the numerical value of the evaluation with which he or she can make an objective and reliable decision.

3 Methodological approach

The complexity of urban areas lies in the interaction of their social, ecological and physical systems (Markolf et al. 2018), and cultural aspects are also relevant (Quesada-Ganuza et al. 2021). In cities, the interaction amongst settlements and infrastructures, characterized by the continuous interaction of multiple functional systems, increases the difficulty to understand and assess climate change risks (Dodman et al. 2022). There are several ways to address this complexity in literature, with the main one being a differentiated approach for specific systems and sectors within the city, that also influences the fragmentation of the management and adaptation policies (Dodman et al. 2022). Nevertheless, an overview of recent literature shows a shift of mind-set in the subject, tending to a more holistic approach to climate change impacts, losses and damages, as urban processes interact, considering more complex risks (Fraser et al. 2020; Simpson et al. 2021). To achieve an understanding of this level of complexity, more complex and detailed models that provide an insight into a smaller scale are necessary.

Complex systems such as historic areas provide a large and varied amount of data, heterogeneous in format, scale and usability (Egusquiza et al. 2018). This information is of public access and can be used to assess the characteristics and, therefore the vulnerability, of the components of historic areas such as buildings and public spaces. As urban components share similarities, typologies can be created through their shared characteristics, to determine sample assets that provide a statistical overview. Furthermore, the organization of this data in a replicable and visual way, and its use for an index that provides a comparison of risk and vulnerability will widely facilitate decision-making and the prioritization of intervention in historic areas.

This chapter proposes a methodology for risk assessment, based on the characterization of buildings and urban space based on their vulnerability to heat waves and urban heat island effect.

3.1 Scope, structure of the methodology and requirements

As concluded by the state of the art review, the lack of research on the heat wave risk assessment for historic areas is a noticeable gap in knowledge (Quesada-Ganuza et al.

2021). The main objective for this chapter, hence, is to develop a holistic and multi-criteria methodology for risk assessment of historic urban areas towards heat waves. This methodology should provide support for the prioritization of future adaptation actions, using a holistic perspective to identify vulnerabilities and risks in historic urban areas. The first requirement for this methodological approach will be, therefore, to provide a framework for the integration of cultural heritage and historic urban areas into wider risk management plans for urban areas and adaptation plans and policies for climate change.

The framework and the definitions used as base for this work are the ones from the IPCC defined on the conceptual framework of this thesis (IPCC 2014a). Following the definition of the European Climate Adaptation Platform Climate-ADAPT for climate change vulnerability and risk assessments (European Commission 2010), we consider as methodologies the ones built upon, information on current climate conditions and future scenarios, including future slow on-set and extremes events; an assessment of potential impacts of climate extremes and climate change on potentially vulnerable sectors and an analysis on underling factors and trends that are influencing climate risks. Based on the data and analysis, an assessment methodology should summarize the most relevant risks and vulnerabilities for a sector or across sectors, focusing on identifying critical impacts and related vulnerabilities within the system.

Vulnerability and risk assessment methodologies are founded onto the use of individual or composite indicators that generate information about non-measurable conditions and enable to compare differently measured data (Kalisch et al. 2014). To begin a risk assessment, the first steps are to define the objectives (why), what system is being analysed (who/what; in this case the historic urban areas), the stressors/hazard (to what; in this case, heat waves) and the time horizon (when) Figure 18. Development of indicators (Adapted from (UNESCO 2010)) (Apreda, D´Ambrosio, and Di Martino 2019; GIZ 2013). This methodology aims to assess first the vulnerability and then the risk that heat waves present for both buildings and urban spaces composing historic urban areas, proposing an impact chain that approaches both from a holistic perspective. The proposed indicators and characterization are thought taking into consideration all kinds of urban areas, to promote their integration at city scale and not stay isolated in historical areas.

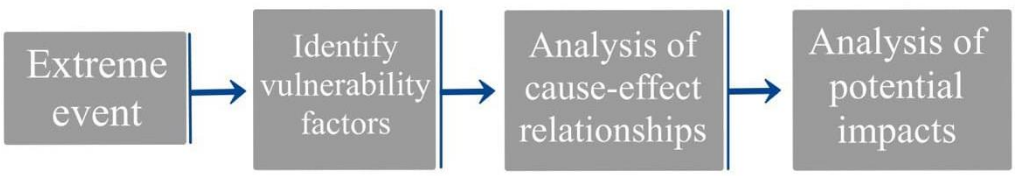


Figure 18. Development of indicators (Adapted from (UNESCO 2010)).

As previously mentioned, this work defines historic urban areas addressing the system from the twofold perspective or an urban area and a historic area. The indicators derive mainly from literature review, either from and urban perspective, or weathering of historic materials. For the identification of the impact chain, first the extreme event will be identified, in this case heat waves and as a consequence the urban heat island effect. Secondly, the vulnerability factors will be identified providing an analysis of the cause-effect relationships that those factors have with the extreme event. As a final step the potential impacts will be identified (Figure 18), different iterations of this process through literature review will provide the indicators for the assessment. For a holistic approach and a multidisciplinary perspective, the assessment of every system need to be addressed, distinguishing between social and economic, cultural, governance (services and resources) and physical (gathering tangible characteristics of all infrastructures, elements and buildings). For a more broad and replicable methodology, the system of historic urban areas was analysed as an urban system upon which the historic urban grid overlaps (Figure 19).

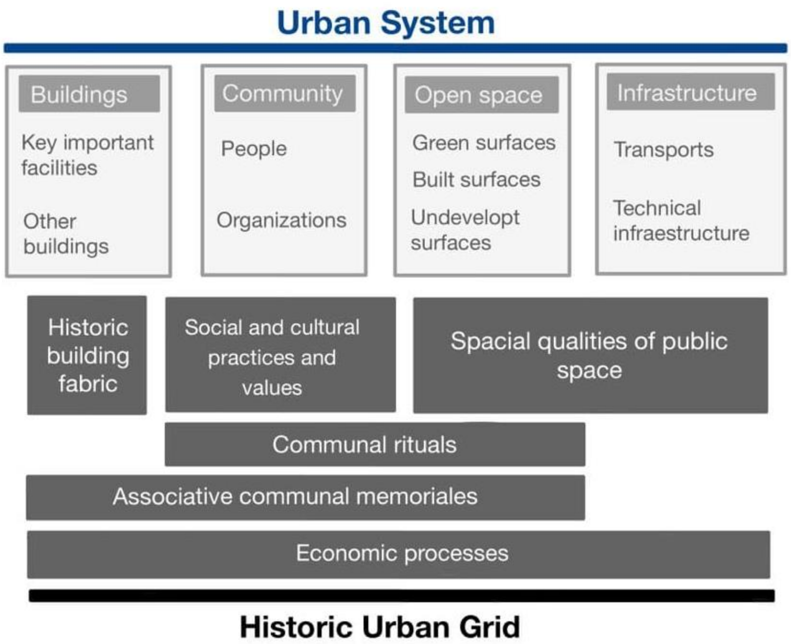


Figure 19. Framework developed for the analysis of historic urban areas.

Hence, and consequently to the groundwork explained in the conceptual framework of this thesis, the indicators are a result of characterizing the potential impacts of heat waves and the urban heat island on the elements that conform the historic urban area. From this approach, combined as mentioned with the AR5 framework from the IPCC (IPCC 2014a) the impact chain would be as shown in Figure 20 and the indicators divided into hazard, exposure and vulnerability. The main receptor for this assessment will be, in conclusion, the buildings and the public spaces, in a twofold approach, considering their physical, cultural, socio-economic and environmental characteristics when assessing their vulnerability to heat waves. This means that even if the main receptors are the buildings/ urban spaces themselves, not only their physical degradation from heat wave conditions will be taken into consideration. The thermal comfort will also be a main consideration, necessary for a holistic perspective, for the impact it has on the users and the effect on the use and, therefore, on the socio-economic, environmental and cultural aspects of both buildings and urban spaces.

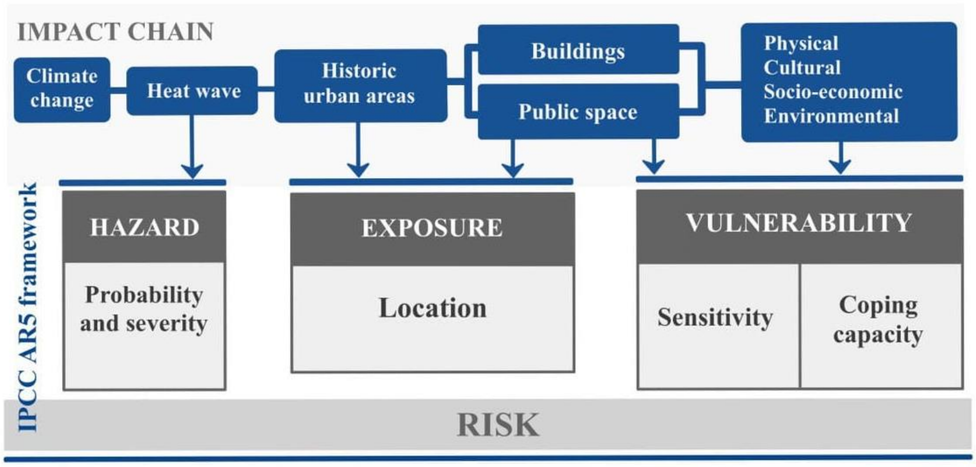


Figure 20. Relation between IPCC AR5 framework for risk assessment and the proposed impact chain for historic urban areas.

In conclusion, the methodological approach provides a data model for historic urban areas that considers risk and vulnerability following the latest approaches to climate change, and structures the information to provide an accessible and replicable framework for decision-making and the prioritization of interventions. The methodology focuses on the evolution and definition of vulnerability indicators, the exposure of the areas to the hazard and contextualizes it to historic areas and urban heritage. To accomplish this goal, the following requirements for the methodological approach are stablished:

REQUIREMENTS

REQ01	Integrate the latest state of the art of climate change concepts and risk assessment with the management and value of urban heritage
REQ02	Ensure a holistic approach through the assessment of all systems within the historic urban area
REQ03	Use a multiscale approach integrating urban and building level
REQ04	Allow an iterative approach and structure of the information for an updated decision-making process
REQ05	Ensure replicability and the use of public data for an accessible model
REQ06	Ensure a visualization of the results that facilitates the decision making process and the prioritization of interventions

Table 4. Requirements for the methodological approach.

To facilitate the intervention strategies and decision-making process, the methodological approach is provided with a categorization on top of a risk assessment that will model the historic urban area towards heat waves and the urban heat island effect.

3.2 Vulnerability assessment

The first step for any decision making towards adaptive strategies to climate change is a vulnerability assessment. As seen in the state of the art review that opens this thesis, there is a lack of holistic approaches when it comes to risk assessment of historic areas, especially considering heat waves (Quesada-Ganuza et al. 2021). Even when looking at other hazards, most approaches consider mainly physical damage to the buildings, not taking into consideration other characteristics or elements. Other than a lack of studies that tackle heat waves, there is a need for a methodology that considers historic areas from a holistic perspective, considering the wide range of factors that determine the buildings conditions, including the ones that affect its inhabitants and its cultural value within the area. Furthermore, the characteristics of the urban spaces that compose the urban grid alongside buildings have a huge influence on the urban heat island effect, so they should be consider as a receptor. Therefore, the proposed methodology will assess both building and urban spaces, characterizing their socio-economic and environmental aspects as well as the physical ones when considering their vulnerability.

When developing adaptation strategies for historic areas, a characterization of the elements into assessment that provides a classification is needed. A statistical overview of the historic area, of both buildings and urban spaces and their vulnerabilities will provide help to stablish the magnitude and prioritize interventions to minimize the impact of heat waves. For this, the integration and visualization of the data and the results on a replicable and accessible model is a main requirement.

3.2.1 Vulnerability assessment with MIVES

As MIVES will be used for the development of the proposed methodology, it will be formed by a hierarchic structure that is composed of three levels: requirements, criteria, and indicators. Criteria cluster measureable aspects of sensitiveness and adaptive capacity, and then each criterion is divided into indicators, that compose the last level of the requirements tree.

Following the MIVES approach set in chapter 2, the definition of the problem and decision to be taken is the first step. The scope for this methodology is to identify, objectively, buildings and public spaces as elements of the historic urban area, that are more vulnerable, and, therefore, more at risk to heat waves and the urban heat island effect.

Requirements tree

As explained on chapter 2, the requirements tree within MIVES is a hierarchic structure that defines displays and organises the characteristics of the vulnerability and risk assessment. It is usually composed by three levels: requirements, criteria and indicators (Pujadas et al. 2017). The last level, composed by the indicators, consider concrete and measurable aspects that feed the first two levels, namely requirements and criteria, that define more general and qualitative aspects.

As the requirements tree defines the objectives for the decision making process, in this case, it was designed following the IPCC approach presented in chapter 2. This approach is the most commonly used when assessing the impacts of climate change and provides a framework that is compatible with existing methodologies and adds value to the existing knowledge. Two requirement trees will form this methodology, one for buildings, and one for public spaces.

This first section will provide the requirements tree formed by the sensitiveness and coping capacity of the elements as the two main requirements, followed by the criteria and indicators. The following 3.3 section will add the exposure and hazard requirements to provide the risk assessment.

Vulnerability of buildings

The degree to which a building is affected by a heat wave event is assessed by the sensitiveness requirement. As depending on the characteristics of the building its response to the impact will vary, several aspects are considered to measure its sensitivity with a holistic perspective. Therefore, the following criteria are defined considering the characteristics of the buildings: environmental, social, physical, economic and cultural value. (Figure 21).

The environmental sensitivity of the building refers to the characteristics of the immediate surrounding of the building that affect its thermal behaviour, and, therefore, the thermal comfort inside. In this case, the solar radiation of the envelope and the acoustic pollution that surrounds the building where chosen as the indicators. The solar radiation heats the envelope of the building, affecting the thermal comfort inside. The acoustic pollution surrounding the building is proven to reduce the willingness of the inhabitants to open the windows, and therefore, the ability to ventilate the interior of the building during the hours of less heat (Núñez Peiró et al. 2020).

The social sensitivity criteria indicates the characteristics of the inhabitants that makes them more sensitive to heat waves. For this, three indicators have been defined, the density of the population residing within the building, the amount of vulnerable population than can suffer adverse consequences from reduced thermal comfort, and the existence and amount of insulation in the envelope of the building.

For the physical sensitivity criteria, that considers the degradation of the building from heat wave conditions, two indicators are defined: date of construction and state of conservation. The date of construction provides the historical typology and therefore is linked to materials that are more or less sensitive to degradation from temperature and humidity extremes.

The economic and cultural value criteria are composed by one indicator each. Economic sensitivity will be measured by the primary use of the building, considering the effect that reduced thermal comfort inside can have on it, affecting its normal use. For cultural value, the link of the building to historical events or traditions will be considered.

As for the coping capacity requirement, it refers to the ability of the system, in this case the building, to assume the potential impact of the extreme event in a very short period. In this case, its composed of two criterion, each of them considering one indicator. The first one is accessibility of the buildings, with the indicator being the presence of an elevator. This considers the possibility of evacuating potential victims of heat strokes or similar health problems caused by heat wave conditions. In the case of the second criteria, cultural value, it considers protection level as an indicator. Protection level of buildings in historic areas limit the interventions and the possible solutions that can be implemented to mitigate the impact of heat waves on buildings and their inhabitants.

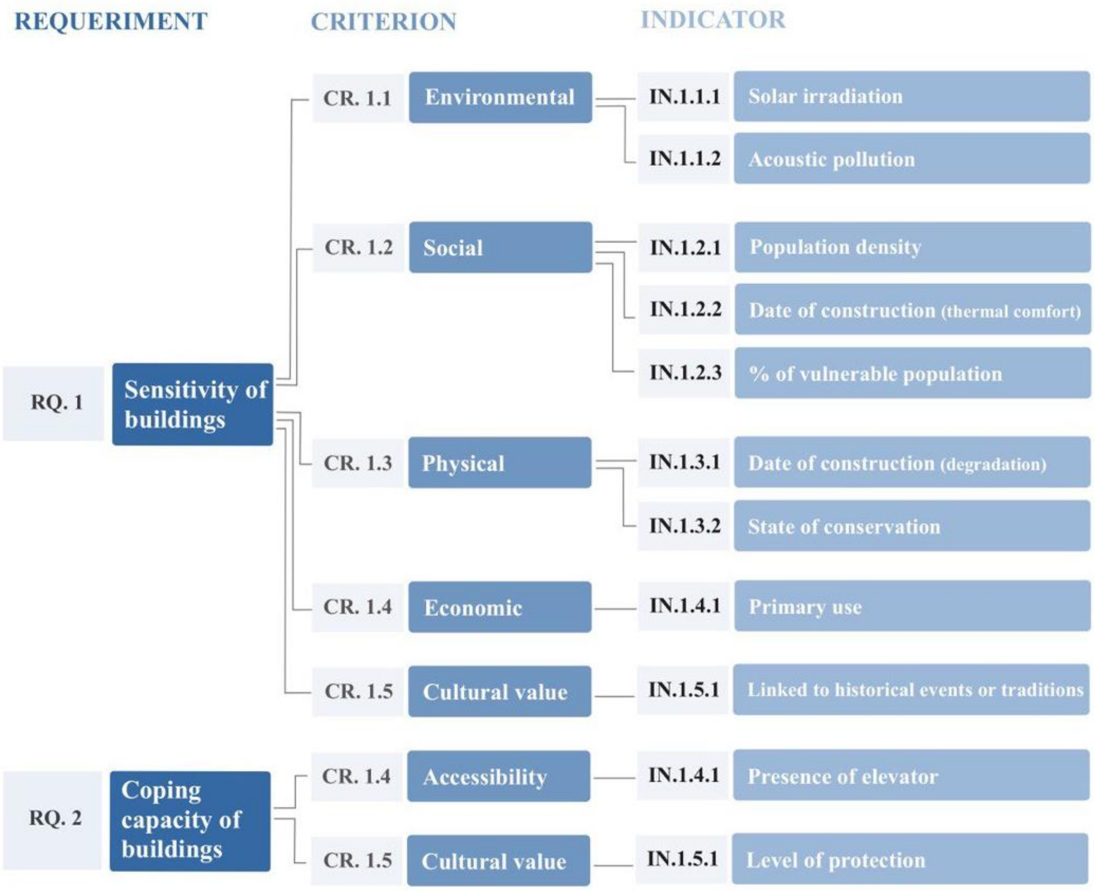


Figure 21. Buildings vulnerability, decision tree. Requirements, criteria and indicators.

As shown in Figure 21, the requirements tree developed for the vulnerability of buildings is divided into 7 criteria and 11 indicators.

Vulnerability of public space

The sensitiveness of public spaces, such as streets or squares to heat waves conditions vary depending on their physical, environmental and socio-cultural characteristics. This characteristics affect the thermal comfort within this spaces and, hence, the people using them. Therefore, the sensitiveness of public spaces is composed of three criteria, physical, environmental and socio-cultural, as shown in Figure 22.

Physical criteria is composed of the indicators that characterize the physical characteristics of the space, albedo, Normalized Difference Vegetation Index (NDVI), and Sky View Factor (SVF). Albedo is the fraction of incoming radiation that a surface reflects, with values from 0 to 1 for lowest and highest reflection, respectively (Erell, Pearlmutter, and Boneh 2012; Andrés-Anaya et al. 2021). NDVI is a simple graphical indicator used to analyse remote sensing measurements, often from a satellite imagery, assessing the presence and density of vegetation present in an area. Finally, SVF is main parameter in determining the phenomenon known as urban canyon (Gartland 2010), it indicates the proportion of an urban space related to heat storage (Dirksen et al. 2019).

Environmental criteria has as indicators solar radiation and air pollution. Intense solar radiation is a common indicator when assessing heat waves, as more hours of direct solar radiation is directly linked to lower thermal comfort. Research shows an increase in ozone levels under conditions such as high temperature, intense solar radiations, and long sunshine hours, all specific meteorological characteristics linked to heatwaves (Pyrgou, Hadjinicolaou, and Santamouris 2018), with high ozone levels being dangerous for human health (Stedman 2004).

For socio cultural criteria, two indicators are considered, relevance of the space and its link to historical events or traditions. Both this indicators measure the amount of people using the space and its relevance to life within the historic area, being, therefore worst affected by heat waves conditions and a reduction in thermal comfort. The relevance of the space is measured by the number and density of ground floor commercial activity within a public space.

For the coping capacity requirement in the case of the public spaces, one criteria measure their ability of responding to the event on a short period of time, accessibility. In the case of historic areas, streets tend to be very narrow, so accessibility in case of an emergency is an important consideration. Hence, the indicator for these criteria is if the space is accessible for firefighters, in case of a fire (more frequent during hotter periods) or the need to evacuate a person victim of a heat stroke or similar health problems caused by heat wave conditions (Sobre et al. 2003; Anderson and Bell 2011).

Therefore, the requirements tree for public space vulnerability (shown in Figure 22) is divided in 4 criteria and 8 indicators.

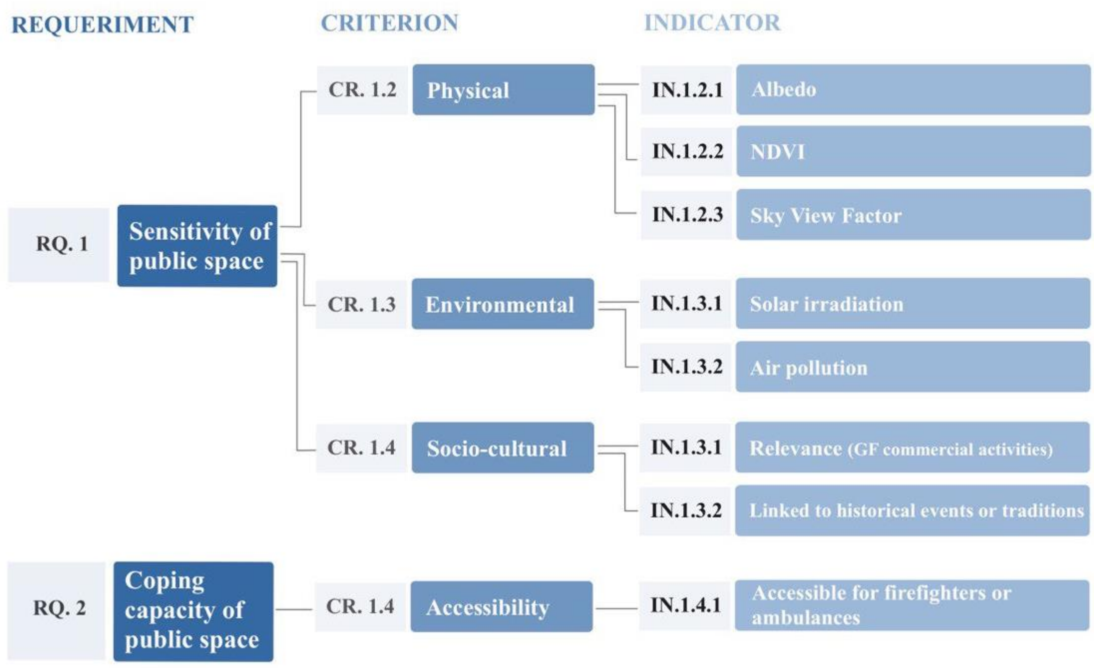


Figure 22. Public spaces vulnerability, decision tree. Requirements, criteria and indicators.

3.2.2 Development of indicators and establishment of values

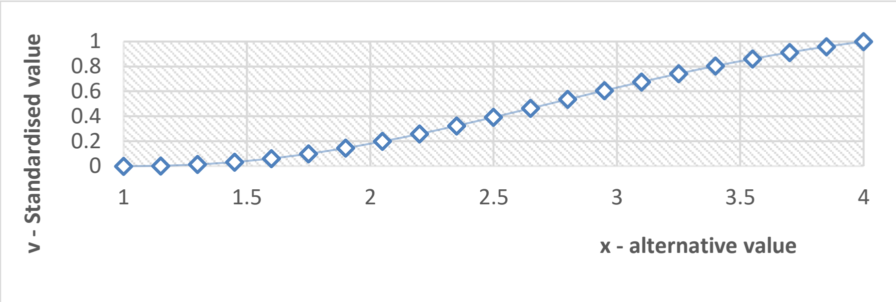
In this section each indicator will be broken down and justified, and is value stablished using the MIVES methodology explained in chapter 2. It will be divided and organized following the previously defined requirements trees, first sensitivity and coping capacity of buildings, followed by the same for public spaces. For the evaluation of the alternatives, a panel of 20 experts was consulted, and the mean of their responses was used to evaluate and weight the indicator and the criteria.

Indicators for the vulnerability of buildings and their value

Solar radiation

Direct solar radiation heats the envelope of a building, affecting the thermal comfort inside. This indicator was calculated (as is explained in the development of the data models for the case studies in the following chapters) using a shadow generator that generates pixel wise shadow analysis using ground and building digital surface models (DSM) (Lindberg et al. 2018). This value varies from 0 (total shadow throughout the day) and 1 (complete solar exposure throughout the day). Four alternatives were set for this indicator, <0,2 very low solar radiation, 0,2-0,4 low solar radiation, 0,4-0,7 medium solar radiation and 0,7-1 high solar radiation.

The following value function in Figure 23 represents the value of each alternative.



Xmin	1
Xmax	4
P	2.2
K	0.01
C	0.28

Figure 23. Shape, tendency and minimum and maximum values for the solar radiation indicator for buildings.

The following table shows the value assigned to each alternative:

Solar radiation		VALUES
Very Low	<0.2	0.00
Low	0.2 to 0.4	0.20
Medium	0.4 to 0.7	0.60
High	0.7 to 1	1.00

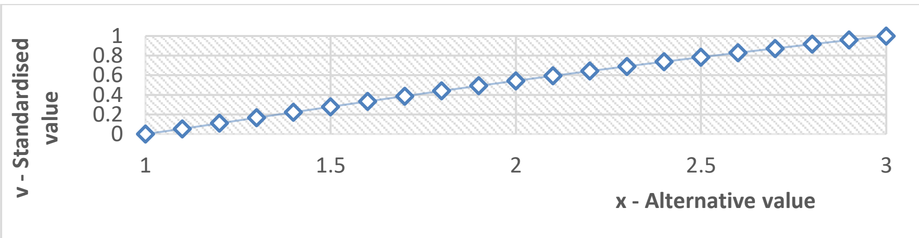
Table 5. Values of the solar radiation indicator.

Acoustic pollution

This indicator measures the acoustic pollution in the area close to the building. The acoustic pollution surrounding the building is proven to reduce the willingness of the inhabitants to open the windows. and therefore, the ability to ventilate the interior of the building during the hours of less heat (Núñez Peiró et al. 2020; McAlexander, Gershon, and Neitzel 2015). This situation, therefore, condensates more heat within the dwellings surrounded by higher street noise.

A literature analysis was carried out to define the thresholds for noise more common in urban settings (McAlexander, Gershon, and Neitzel 2015; Jakovljevic, Paunovic, and Belojevic 2009; Jarosińska et al. 2018) and the noise maps and regulations more frequent in the case studies were consulted. With these conclusions the alternatives where set as < 50 dBA low, 50 dBA to 70dBA medium, > 70 dBA high.

The following value function in Figure 24 represents the value of each alternative.



Xmin	1
Xmax	3
P	1.05
K	1
C	4

Figure 24. Shape, tendency and minimum and maximum values for acoustic pollution indicator in buildings.

The following table shows the value assigned to each alternative:

Acoustic pollution		VALUES
Low	< 50 dBA	0.00
Medium	50 dBA to 70dBA	0.54
High	> 70 dBA	1.00

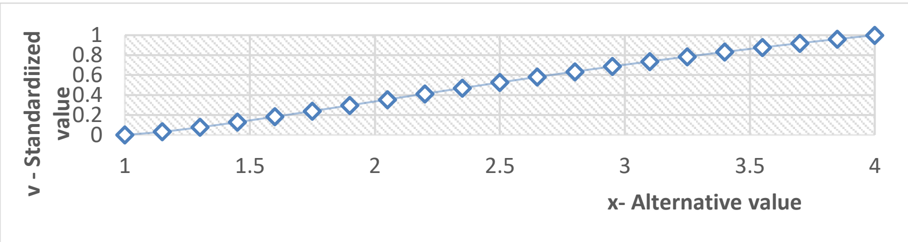
Table 6. Values of the alternatives of the acoustic pollution indicator.

Population density

This indicator considers the density of the population living inside a building. As the inhabitants of a building not only generate heat by themselves, the activities they carry inside the building also generate heat, all of it considered anthropogenic heat. Therefore, the higher the population density (inhabitants per habitable square meter), the higher the anthropogenic heat generated within the building.

For this indicator 4 alternatives were set, 0 inhabs/sqm as empty buildings, higher than 0 but lower than 0.02 inhabs/sqm low density, between 0.02 and 0.5 inhabs/sqm medium density and higher than 0.05 inhabs/sqm a high density.

The following value function in Figure 24 represents the value of each alternative.



Xmin	1
Xmax	4
P	1.5
K	0.4
C	2

Figure 25. Shape, tendency and minimum and maximum values for density of inhabitants in buildings.

The following table shows the value assigned to each alternative:

Inhabitants per sqm of residential area in the building		VALUES
Empty	0	0.00
Low	< 0.02 habs/m2	0.26
Medium	0.02 to 0.05 habs/m2	0.61
High	> 0.05 habs/m2	1.00

Table 7. Values of the alternatives of the density of inhabitants in buildings.

Date of construction (thermal comfort)

This indicator assesses the thermal behaviour of the façade during a heat wave depending on the date of construction. As there is no available data regarding the specific envelope materials and amount of isolation present in each building, typologies were developed using the date of construction of the buildings. This indicator varies depending on the case study, as the historical typologies will be different depending on the construction traditions on each historic area. For this thesis, the case studies of Bilbao and Naples were chosen. Although this indicator will be developed and use on both case studies on chapters 4 and 5, for this the example of the typologies developed for Bilbao will be shown.

The alternatives set for this case were five.

- Buildings from before the XVI century with a wood and brick structure, considered to have low thermal inertia, no isolation.
- Buildings dated between XVI century and 1920, assumed to be natural stone masonry buildings, therefore, no isolation will be present, but masonry has some thermal inertia.
- Buildings dated between 1920 and 1970 are mostly simple brick façades with no isolation.
- The buildings dated between 1970 and 2006 composed of double layer brick façades with none or low isolation.
- The buildings dated after 2006, year when the construction code for Spain was unified (Ministerio de la Vivienda 2006), are composed of envelopes with a minimum of 6cm of isolation present.

In this situation there is no value function as there are no middle values, each alternative has a specific value that does not follow a function.

The average weight vector proposed by the experts' evaluation is shown in Table 8.

Date of construction of the building	VALUES
> 2006	0,00
1970 to 2006	0.20
1920 to 1970	0.60
XVI to 1920	0.40
< XVI century	1.00

Table 8. Weights of the date of construction indicator.

Percentage of vulnerable population

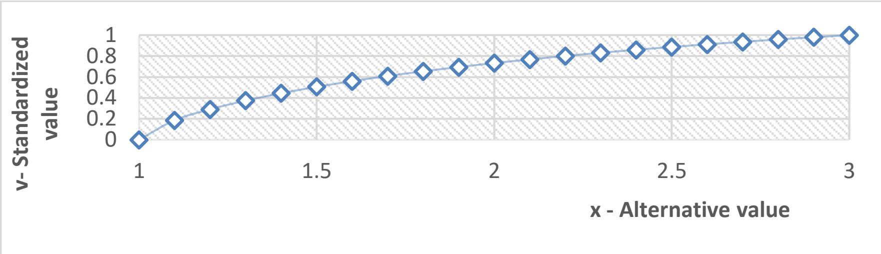
This indicator evaluates the amount of inhabitants of a building that have characteristics that make them more vulnerable to heat wave conditions. As the only data available is the age of the residents divided between people younger than 65 and older, that threshold was used to divide the population.

Thermal sensation is derived from thermal comfort and is key to a heat wave event. A human body at rest generates around 100 W of metabolic heat (as well as any absorbed solar heat), and if the ambient temperature is higher than the optimum central temperature of the human body (around 37 °C), the human body cannot dissipate heat (Matthaios Santamouris 2019). On the other hand, sweating, the main process by which the human body regulates temperature, becomes less effective if the relative humidity is high, resulting in the accumulation of heat within the body and, therefore, an increase in morbidity and mortality. Heat related mortality specially rises amount elderly people (older than 75 years old), who are at greater risk of mortality than the younger population

(COMMISSION and ENVIRONMENT 2011; Anderson and Bell 2011; Sobre et al. 2003)

Three alternatives were therefore set depending on the percentage of people older than 65 (because of the available data) present on the building, low for buildings with less than 25% of residents over 65, medium for between 25 and 40% and high for over 40% of inhabitants being over 65 years of age.

Following this and the experts' evaluation, the value function in Figure 26 represents the value of each alternative.



Xmin	1
Xmax	3
P	1
K	2
C	4

Figure 26. Shape, tendency and minimum and maximum values for percentage of older population in the building.

The following table shows the value assigned to each alternative:

population older than 65 years of age		VALUES
Low	< 25%	0.00
Medium	25% to 40%	0.62
High	> 40%	1.00

Table 9. Values of the alternatives of percentage of older population living in the building.

Date of construction (linked to degradation of materials)

This indicator uses the available data of the year of construction of the buildings to link it to the risk of degradation of materials under heat wave conditions. For the development of this indicator, the development of constructive typologies was necessary, as there is no data available regarding the constructive characteristics of each individual building. This typologies and the alternatives derived from them were developed by a literature review of the historic material most vulnerable to heat wave conditions (high heat, humidity extremes and high solar radiation) and linked to the building typologies found in the case studies regarding their year of construction.

A literature search showed that the historic materials most vulnerable to heat wave conditions (Sabbioni et al. 2010) are porous stones and fire clay bricks, coloured timber, traditional mortars and historic wall coverings and polychromies (E. Sesana et al. 2021; Nijland et al. 2009; Leissner et al. 2015). There is also literature linking the faster degradation of stained glass windows under heat wave conditions, especially in areas with pollution sensitive to heat (Melcher and Schreiner 2010; Pyrgou, Hadjinicolaou, and

Santamouris 2018) (as near surface ozone, this is farther developed later in the indicator for air pollution on public spaces).

In the case of buildings built in periods that used wooden structures and decorative elements are considered, they are vulnerable to fungal attack in the case of high heat and humidity, and are degraded by increased heat and solar radiation in the case of coloured timber ((Nijland et al. 2009; Huerto-Cardenas et al. 2021)). Buildings from periods characterized by the use of porous stones, as natural stone masonry or fire clay bricks, are prone to salt damage derived from higher heat and variation of humidity cycles (Camuffo 2019; Leissner et al. 2015; Lubelli et al. 2018). Historic wall coverings and polychromies are shown to be degraded by increased solar radiation and higher temperatures and humidity (Nijland et al. 2009; Leissner et al. 2015).

Therefore, as it was done for the indicator that linked thermal behaviour of the buildings and their year of construction, it varies depending on the case study and will be further developed on chapters 4 and 5. For this Bilbao will be used as an example. For the typologies created in this indicator the degradation of materials that characterize the different periods have been considered.

As said before, the alternatives here will vary depending on the study case, but as an example for Bilbao:

- Buildings from before XVI century with a wood and brick structure contain a lot of timber elements and historic wall coverings.
- Buildings from between XVI century and 1850 are commonly natural stone masonry buildings with timber decorative elements, mostly coloured, painted, and with possible presence of polychromies and traditional wall coverings.
- Buildings from between 1850 and 1920 are also natural stone masonry buildings or with fire clay brick façades, some with timber decorative elements, mostly coloured and painted.
- In buildings from between 1920 and 2006 some porous stone like bricks may be present, alongside more modern materials.
- Buildings from 2006 or after are built with modern materials.

In this context there is no value function as there are no middle values, each alternative has a specific value that does not follow a function.

The average weight vector proposed by the experts' evaluation is shown in Table 10

Date of construction of the building	VALUES
> 2006	0.00
1970 to 2006	0.20
1920 to 1970	0.60
XVI to 1920	0.40
< XVI century	1.00

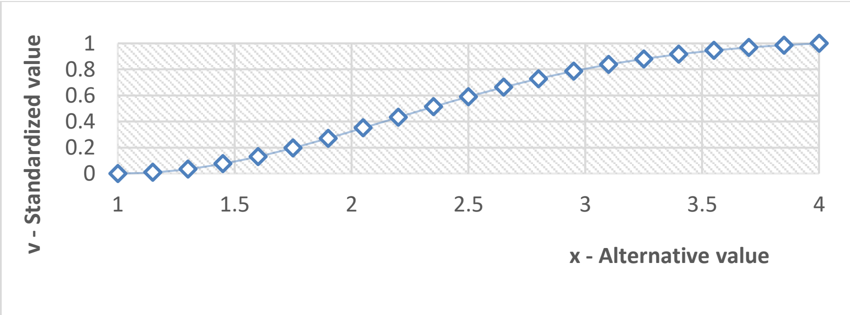
Table 10. Values of the alternatives of date of construction of the building.

State of conservation

This indicator refers to the state of conservation of each building. As for the degradation of materials, under heat wave conditions the focus is on the envelope. The state of the buildings envelope has an influence in the further degradation of the building, as a worst condition represents a greater sensitiveness. The following alternatives were stablished for this indicator:

- Very bad / ruin. A completely deteriorated building. Serious damage to most elements and could include partial collapse of some structures.
- Bad. The building presents deterioration, some elements are in poor condition and there is danger of material detachment.
- Fair. Presents occasional and limited damage that does not need immediate intervention.
- Good. No visible damage, all elements seem in good condition.

Following this and the experts' evaluation, the value function in Figure 27 represents the value of each alternative.



Xmin	1
Xmax	4
P	2
K	1.5
C	2

Figure 27. Shape, tendency and minimum and maximum values for state of conservation of the buildings.

The average weight vector proposed for the alternatives by the experts' evaluation is shown in Table 11:

State of conservation of building	VALUES
Very bad /ruin	0.00
Bad	0.36
Fair	0.77
Good	1.00

Table 11. Values of the alternatives of the state of conservation.

Primary use of the building

This indicator assesses the sensitivity of the primary use of the building. This is, the importance of the main service the building provides and the disruption to it that a reduced thermal comfort would imply. For the experts evaluation it was asked to consider when a disruption of use and the reduction of thermal comfort inside the building would be more relevant and worse for the area. For example social use (school, medical centre kindergarten etc.), cultural (museum, church), industrial (workshop, factory) etc.

For the value assignment, the impact of reduced thermal comfort on the main activity was evaluated to provide 4 alternatives. The maximum value is given to the use considered more critical, and therefore, more sensitive.

The average weight vector proposed for the alternatives by the experts' evaluation is shown in Table 12

Primary use of the building	VALUES
Residential	0.82
Industrial	0.48
Public use (social/cultural)	0.84
Touristic	0.43

Table 12. Values of the alternatives of the primary use of the building.

Building linked to historical events or traditions

This indicator assesses if a building if linked to historical events or traditions within the area. This link makes the building more sensitive, as its degradation or a reduced thermal comfort inside affecting its main use could have a relevant impact in the sense of place of the historic area.

This is a dichotomous indicator (yes or no), part of the normative indicators, is one that considers the existence of a referent in an specific situation.

This information is not usually available as directly accessible data, but can be gathered through a historical evaluation of the area or through the knowledge of local stakeholders.

The maximum value is therefore given to buildings that are linked to local traditions or historical events relevant to the sense of place of the area.

Building linked to Historical events or traditions	VALUES
Yes	1
No	0

Table 13. Values of the alternatives of the link of a building to historical events or traditions.

Accessibility. Presence of elevator

This is a coping capacity indicator; these indicators refer to the lack of ability of the system, in this case the building, to assume the potential impact of the heat wave in a very short period. The first criteria is accessibility of the buildings, with the indicator being the presence of an elevator. This indicator considers the possibility of evacuating potential victims of heat strokes or similar health problems caused by heat wave conditions, for which the presence of an elevator is crucial.

As the previous one, his is a dichotomous indicator (yes or no). Coping capacity is measured negatively (lack of), therefore, the maximum value is given to the absence of an elevator.

Presence of elevator	VALUES
Yes	0.00
No	1.00

Table 14. Values of the alternatives of accessibility.

Cultural value. Protection level.

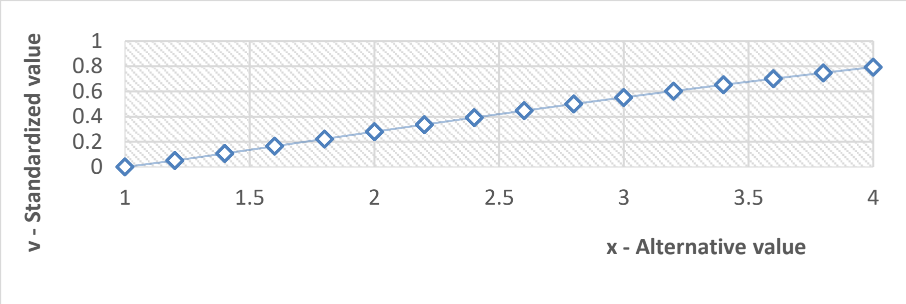
This indicator assesses the protection degree that the building has under the laws that manage the conservation of cultural heritage, either municipally or at a state or national level. In this situation, this indicator evaluates the possible mitigating interventions or solutions that can be applied to the building in a short period of time to improve thermal comfort and mitigate the effects of the heat wave conditions. As a protected or listed building will probably have a limited amount of allowed interventions, the highest level of protection will probably exclude all possible solutions that can be implemented. In this case, as is a coping capacity indicator is measured negatively, meaning, that a highest protection that limits most interventions gets the maximum value (1).

This regulation and levels vary depending on the country and region, but are usually comparable amongst each other. For this, 5 alternatives were created using the regulations applied in Bilbao, but same levels with different names were used for Naples, hence, the same values apply.

- No protection. Buildings that are not protected nor included in any list of classified buildings, and therefore, no restrictions apply for interventions.
- Low protection. Basic /ambiental. This level of protection corresponds to buildings and constructions of recognizable and protectable value in relation to their environment. The elements in which these values reside are always external elements that support their image.
- Medium protection. Typological. This level of protection corresponds to buildings of recognized individual value. The protected elements refer only to the external envelope of the building. For these buildings, a protection regime has to be defined, limiting the possible interventions on the envelope for their effective conservation.
- High protection. Integral. Buildings and constructions with a recognized individual value are included at this level of protection. Protected elements refer to the exterior as well as to the interior envelope. A protection regime is defined for these buildings, limiting the possible interventions on the external and internal elements of the building, for effective conservation.
- Very high protection. Monument. This level of protection corresponds to buildings and constructions that have been declared of special interest, subject either to their own protection and intervention regimes or to generic and transitory protection and intervention regimes. In all cases, they are subject to compulsory consultations and corresponding authorizations of supra-municipal level. In other words, these buildings are affected by protection decisions, declarations and

procedures promoted at a supra-municipal level, by the competent (Regional or State Administration) authorities in the matter.

Following this and the experts' evaluation, the value function in Figure 28 represents the value of each alternative.



Xmin	1
Xmax	5
P	1.1
K	0.15
C	1

Figure 28. Shape, tendency and minimum and maximum values for the level of protection of buildings.

The average weight vector proposed for the alternatives by the experts' evaluation is shown in Table 15.

Protection level of the building		VALUES
Very High	Monument	0.00
High	Integral	0.28
Medium	Typological	0.59
Low	Basic / ambiental	0.81
None	None	1.00

Table 15. Values for the level of protection of buildings.

The following table summarises the values for each alternative of the indicators regarding the vulnerability of the buildings.

INDICATOR		ALTERNATIVES AND VALUE		
1.1.1	Solar radiation	**Shadow fraction**		**VALUES**
		very low	<0.2	0.00
		low	0.2 to 0.4	0.20
		medium	0.4 to 0.7	0.60
		high	0.7 to 1	1.00
1.1.2	Acoustic pollution	**Acoustic pollution**		**VALUES**
		low	< 50 dBA	0.00
		medium	50 dBA to 70dBA	0.54
		high	> 70 dBA	1.00
1.2.1	Population density	**Inhabitants per sqm of residential area in the building**		**VALUES**
		Empty	0	0.00
		Low	< 0.02 habs/sqm	0.26
		medium	0.02 to 0.05 habs/ sqm	0.61
		high	> 0.05 habs/ sqm	1.00
1.2.2	Date of construction (thermal comfort)	**Date of construction of the building**		**VALUES**
		> 2006		0.00
		1970 to 2006		0.40
		1920 to 1970		0.69
		XVI to 1920		0.56
		< XVI century		1.00
1.2.3	% of vulnerable population	**population older than 65 years of age**		**VALUES**
		low	< 25%	0.00
		medium	25% to 40%	0.62
		high	> 40%	1.00
1.3.1	Date of construction (linked to vulnerability of materials)	**Date of construction of building**		**VALUES**
		> 2006		0.00
		1970 to 2006		0.40
		1920 to 1970		0.69
		XVI to 1920		0.56
		< XVI century		1.00
1.3.2	State of conservation	**State of conservation of building**		**VALUES**
		Good		0.00
		Fair		0.36
		Bad		0.77
		Very bad /ruin		1.00
1.4.1	Primary use	**Primary use of the building**		**VALUES**
		Residential		0.82
		Industrial		0.48
		Public use (social/cultural)		0.84
		Touristic		0.43
1.5.1	Linked to historical events or traditions	**Building linked to Historical events or traditions**		**VALUES**
		Yes		1
		No		0
2.1.1	Elevator	**Presence of elevator**		**VALUES**
		Yes		1
		No		0
2.2.1	Level of protection	**Protection level of the building**		**VALUES**
		Very high	Monument	1.00
		high	Integral	0.81
		medium	Typological	0.59
		Low	Basic / ambient	0.28
		None	None	0.00

Table 16. Summary of the values for each alternative of indicators regarding the vulnerability of buildings.

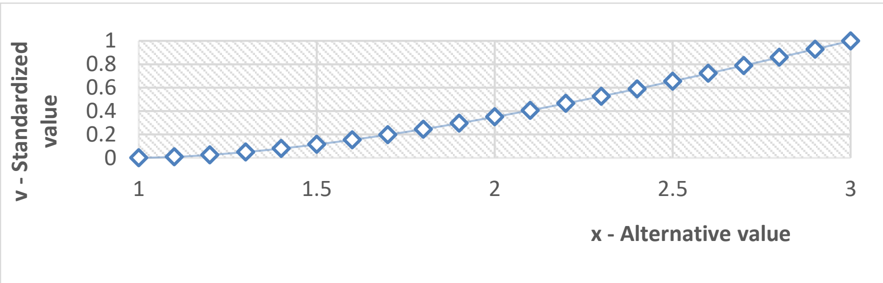
Indicators for the vulnerability of public space and their value

Albedo

The indicator for albedo assesses the amount of solar radiation reflected or absorbed by a surface, as determined by reflectivity of the materials. Albedo is the fraction of incoming radiation that a surface reflects, with values from 0 to 1 for lowest and highest reflection, respectively (Erell, Pearlmutter, and Boneh 2012; Andrés-Anaya et al. 2021). With higher albedo, reflective materials usually appear whiter and are able to absorb less radiation and maintain a lower surface temperature during daytime (Yang, Wang, and Kaloush 2015). During the night, although albedo of materials becomes ineffective due to the absence of solar radiation, as more radiation is reflected during the day, less heat is stored in high-albedo materials compared to conventional ones. This can lead to small reductions of night surface temperature (Synnefa et al. 2008; M Santamouris et al. 2012; Dutta, Basu, and Agrawal 2021). Several studies have found decreases up to almost 10ºC on the maximum surface temperature during very hot days by the use of high albedo materials, or by increasing the albedo of the existing surfaces (Yang, Wang, and Kaloush 2015; Morini et al. 2016; Andrés-Anaya et al. 2021; M Santamouris et al. 2012).

After a literature search and comparison of different studies (Kotak et al. 2015; Touchaei, Akbari, and Tessum 2016; Morini et al. 2016; Yang, Wang, and Kaloush 2015; Andrés-Anaya et al. 2021), the alternatives for the indicator were set as 3, low albedo being a value of less than 0,25, medium being 0,25 to 0,6, and a high albedo being a value higher than 0,6. As a lower albedo represents the most sensitive scenario, the higher value (1) is assigned to it.

Following this and the experts' evaluation, the value function in Figure 29 represents the value of each alternative.



Xmin	1
Xmax	3
P	1
K	3.3
C	4

Figure 29. Shape, tendency and minimum and maximum values for albedo.

The average weight vector proposed for the alternatives is shown in Table 17.

Albedo of the space		VALUES
High	> 0.6	0.00
Medium	0.25 to 0.6	0.70
Low	< 0.25	1.00

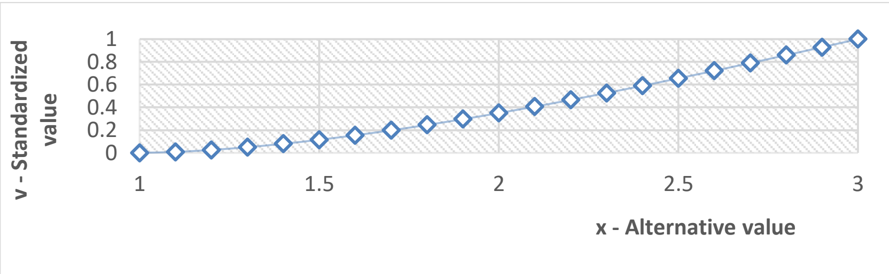
Table 17. Values for albedo.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index or NDVI is one of the most extensively used indexes to differentiate vegetated areas from non-vegetated areas and the density of the vegetation. It transforms satellite image of NIR and Red channels into a single band image with range value between − 1 to + 1. The values of NDVI indicate the amount of chlorophyll content present in vegetation, where higher NDVI value indicate dense and healthy vegetation and lower value indicate and sparse vegetation or bare soil (Tomar et al. 2013; Rani et al. 2018). Negative values of NDVI (values approaching -1) correspond to water. Values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow. Low, positive values represent shrub and grassland (approximately 0.2 to 0.4), while high values indicate temperate and tropical rainforests (values approaching 1) (Grover and Singh 2015; Rani et al. 2018).

Is broadly studied that the presence of vegetation, especially if is denser, is linked to a lower land surface temperature (Weng, Lu, and Schubring 2004; Grover and Singh 2015) and, hence, better thermal comfort in urban areas. Therefore, this index is used as an indicator to measure the presence of vegetation in the historic urban areas, with a higher NDVI representing lower sensitivity. As mentioned before values lower than -0,1 are linked to water (Grover and Singh 2015; Rani et al. 2018), and hence, will be discarded in this case. The alternatives, based on the most broadly accepted values in literature (Weng, Lu, and Schubring 2004; Grover and Singh 2015; Rani et al. 2018):

- Low. Values between -0,1 and 0,2 generally correspond to barren areas without any vegetation.
- Medium. 0.2 to 0.4 represent sparse vegetation.
- High. Values higher than 0,5 that represent denser vegetation.



Xmin	1
Xmax	3
P	1.65
K	0.09
C	1

Figure 30. Shape, tendency and minimum and maximum values for NDVI.

The average weight vector proposed for the alternatives is shown in Table 18

	NDVI	VALUES
High	> 0.5	0.00
Medium	0.2 to 0.5	0.35
Low	< 0.2	1

Table 18. Values for NDVI.

Sky view Factor (SVF)

The SKY View Factor or SVF is the measure of how much sky is visible at a given location and can be used to easily describe as a 2-dimensional metric the 3-dimensional form of the built environment. The SVF has been strongly related to nocturnal Urban Heat Island (UHI) effects, intra-urban air temperature distribution, and thermal comfort (L. Chen et al. 2012; Dirksen et al. 2019).

The SVF is the fraction of visible sky measured between 0 and 1. The short wave radiation within an open space (with a SVF close to 1) reaches the surface without being blocked, while within a more narrow street or urban space (with a SVF lower than one) reflections plays a role and the long wave radiation is either absorbed or reflected by the surface. There are several ways of calculating SVF, either in 2D or 3D. The basic 2D method being:

$$SVF_{2D} = cos\left(arctan\left[\frac{H}{0,5W}\right]\right)$$

Equation 13. Equation for the calculation of SVF in 2D.

Were H is the height of the buildings and W is the wigth of the street Figure 31 (f).

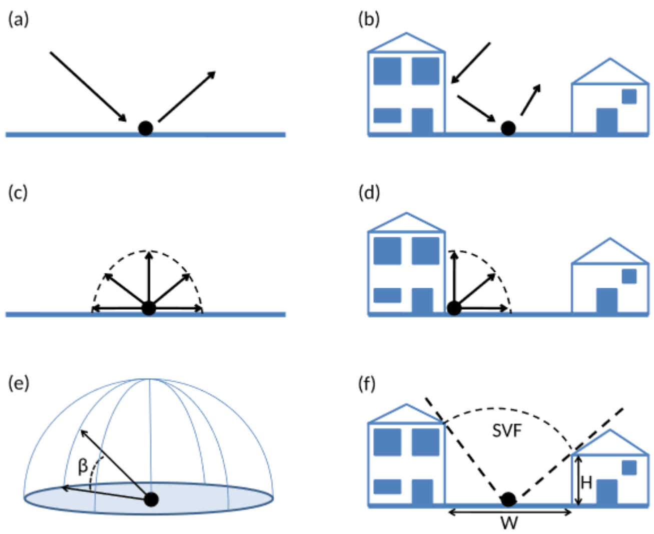


Figure 31. Radiation components in an openfield and street canyon and SVF calculations illustrated. (a) Short wave radiation in an openfield. (b) Shortwave radiation in a street canyon. (c) Emission of long wave radiation in an openfield. (d) Emission of long wave radiation in a street canyon. (e) SVF calculated in 3D; (f) SVF in a 2D street canyon figures are adapted from (Dirksen et al. 2019).

In 3D perspective, visualized in *Figure 31 (e).*, the SVF for a point on a grid is calculated as:

$$SVF_{3D} = \int_{\theta=0}^{2\pi} cos^2\big(\beta(R,\theta)\big)d\theta$$

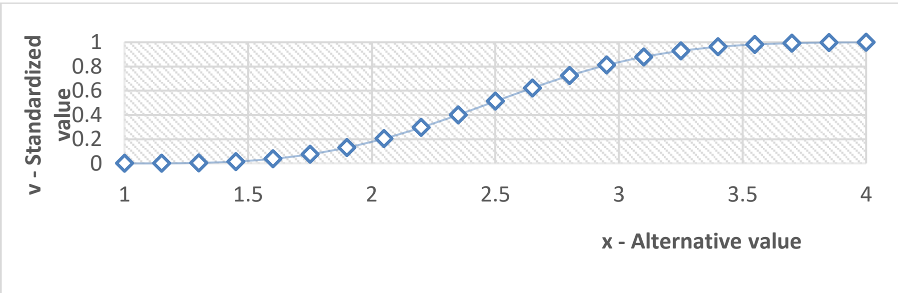
Equation 14. Equation for the calculation of SVF in 3D.

Were β is the angle from the center point to the maximum obstacle height at a maximum distance equal to the constant search radius (R). When integrating this formula over all directions (dθ) from 0 to 2π, the SVF for the full hemisphere is obtained (Dirksen et al. 2019).

In this methodology the calculation method used for the SVF was the SOLWEIG plugging for QGIS, using ground and building digital surface models (DSM) (Lindberg et al. 2018) in the Naples model, and a classical method, using Equation 13and Equation 14 on a GIS model on the Bilbao case study.

The alternatives for SVF were set based on a literature analysis of the most common values linked to an increase on surface temperature at night, producing the urban canyon effect linked to the urban heat island (Eliasson 1996; L. Chen et al. 2012). Low values of less than 0.35 define very narrow streets prone to be urban canyons, medium values of between 0.35 and 0.5 are less narrow spaces that are shown to accumulate some heat, high SVF between 0.5 and 0.65 are less prone to accumulate heat, and SVF values higher than 0.65 define open spaces.

As a lower SVF is linked to an accumulation of heat and a higher temperature at night, the higher sensitivity value (1) will be assigned to the lower SVF (<0.35).



Xmin	1
Xmax	4
P	3.2
K	1.8
C	2

Figure 32. Shape, tendency and minimum and maximum values for SVF.

The average weight vector proposed for the alternatives is shown in Table 19.

SVF		VALUES
Very High	> 0.65	0
High	0.5 to 0.65	0.2
Medium	0.35 to 0.5	0.8
Low	< 0.35	1

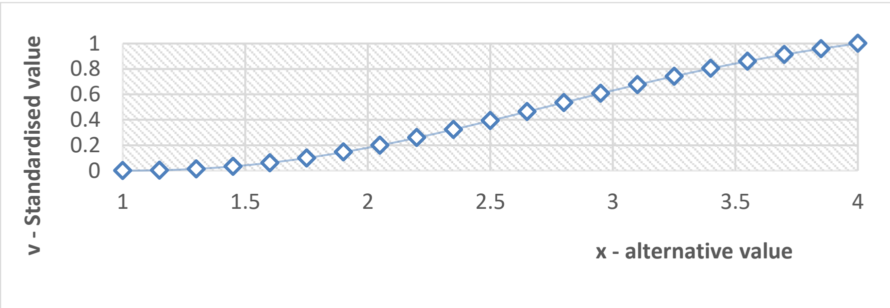
Table 19. Values for SVF.

Solar radiation

Direct solar radiation heats the surfaces of a space, affecting the thermal comfort within. As explained in the solar radiation indicator for the buildings, it was calculated (as is explained in the development of the data models for the case studies in the following chapters) using a shadow generator that generates pixel wise shadow analysis using ground and building digital surface models (DSM) (Lindberg et al. 2018). This value varies from 0 (total shadow throughout the day) and 1 (complete solar exposure throughout the day). Four alternatives were set for this indicator, <0.2 very low solar radiation, 0.2-0.4 low solar radiation, 0.4-0.7 medium solar radiation and 0.7-1 high solar radiation.

As the higher solar exposure represents a higher sensitivity, the maximum value (1) was assigned to the higher solar radiation value (1).

The following value function in Figure 23 represents the value of each alternative.



Xmin	1
Xmax	4
P	2.2
K	0.01
C	0.28

Figure 33. Shape, tendency and minimum and maximum values for the solar radiation indicator for urban spaces.

The following table shows the value assigned to each alternative:

Solar radiation		VALUES
Very Low	<0.2	0.00
Low	0.2 to 0.4	0.2
Medium	0.4 to 0.7	0.8
High	0.7 to 1	1.00

Table 20. Values of the alternatives for solar radiation of public spaces.

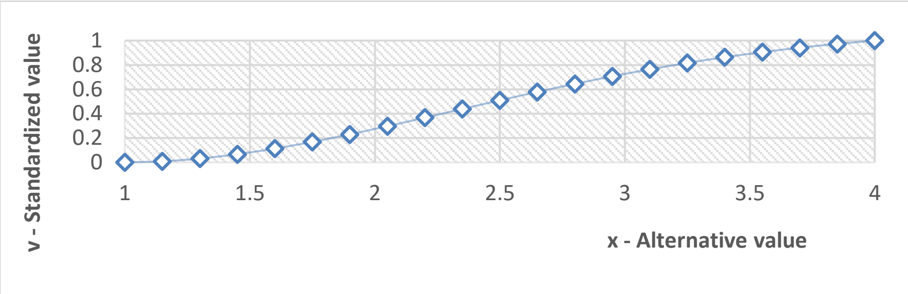
Air pollution (Near surface Ozone O_3)

Research shows an increase in ozone levels under conditions such as high temperature, intense solar radiations, and long sunshine hours, all specific meteorological characteristics linked to heatwaves (Pyrgou, Hadjinicolaou, and Santamouris 2018), with high ozone levels being dangerous for human health (Stedman 2004; Czarnecka and Nidzgorska-Lencewicz 2014). Studies have shown that ozone production accelerates at high temperatures (without changing VOC or NOx conditions) which may be attributed not only to the temperature dependence of chemical reactions, but also to the weak winds which accompany high temperatures and heatwaves and cause the atmosphere to stagnate and built up ozone levels (Stathopoulou et al. 2008). Ozone does not only depend on the quantities of the precursors, but also on the ability of the atmosphere to form or deplete ozone and specifically under favourable meteorological conditions such as high temperature, intense solar radiations, long sunshine hours and low wind speed/direction, all characteristics of heatwaves (Pyrgou, Hadjinicolaou, and Santamouris 2018; Touchaei, Akbari, and Tessum 2016).

For the setting of alternatives, the regulation and research linking near surface ozone levels to health issues was studied. Therefore, the alternatives are very low for concentrations lower than 140 µg/m3, low for between 140 and 180 µg/m3, medium for between 180 and 240 µg/m3 and high for concentrations higher than 240 µg/m3.

This indicator is very hard to use on case studies due to data availability. For its application, a high resolution map of ozone levels would be necessary, with measurements on a few meter scale. This was not available in neither of the case studies, so it was not used. Nevertheless, it was developed for the core methodology and the alternatives were assigned weights.

The following value function in Figure 34 represents the value of each alternative.



Xmin	1
Xmax	4
P	1.9
K	0.4
C	1.2

Figure 34. Shape, tendency and minimum and maximum values for ozone.

The following Table 21 shows the value assigned to each alternative

Ozone levels		VALUES
Very Low	< 140 µg/m3	0.00
Low	140 to 180 µg/m3	0.32
Medium	180 µg/m3 to 240 µg/m3	0.66
High	> 240 µg/m3	1.00

Table 21. Values for Ozone.

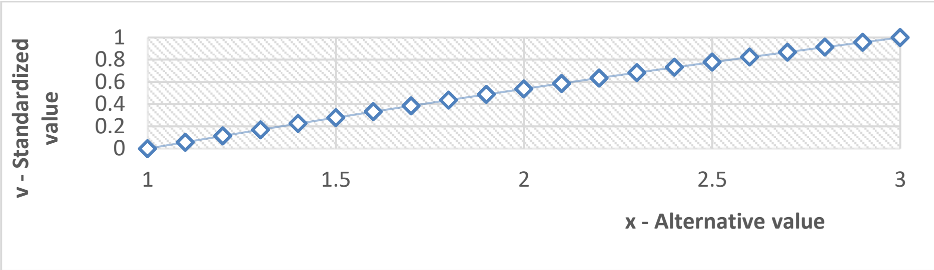
Relevance to life (GF commercial activities on buildings)

This indicator assesses the amount of use a public space sustains, and hence the relevance it has within the historic area. The more people using a street or square, the more sensitive it is to heat wave conditions, due to the impact, both economic and social, the reduce thermal comfort on that space can have.

For the calculation of this indicator, it was used the amount and density of commercial use on the ground floor of buildings. This data is available on some cities, for example Bilbao, showing as an attribute for the buildings the use on ground floor. To measure the density of commercial activity the number of ground floor commercial activity per 100 meters was measured and used as an indicator.

After comparing results on different areas, the alternatives were set as low relevance for the spaces with less than 5 per 100m, medium for between 5 and 15 per 100m and high relevance for the ones with more than 15 per 100 meters.

The following value function in Figure 35 represents the value of each alternative:



Xmin	1
Xmax	3
P	1
K	1.7
C	4

Figure 35. Shape. tendency and minimum and maximum values for relevance of the public space.

The following Table 22 shows the value assigned to each alternative

GF commercial activities on buildings per 100m street / square		VALUES
Low	< 5	0.00
Medium	5 to 15	0.57
High	> 15	1.00

Table 22. Values for the relevance of public space.

Linked to historical events or traditions

As the correspondent one for buildings. this indicator assesses the link of a street or square to historical events or traditions within the area. This link makes the space more sensitive, as its degradation or a reduced thermal comfort affecting its use could have a relevant impact in the sense of place of the historic area.

This is a dichotomous indicator (yes or no), and considers the existence of a referent in an specific situation. This information is not usually available as directly accessible data, but can be gathered through a historical evaluation of the area or through the knowledge of local stakeholders.

The maximum value is therefore given to spaces that are linked to local traditions or historical events relevant to the sense of place of the area.

Space linked to Historical events or traditions	VALUES
Yes	1
No	0

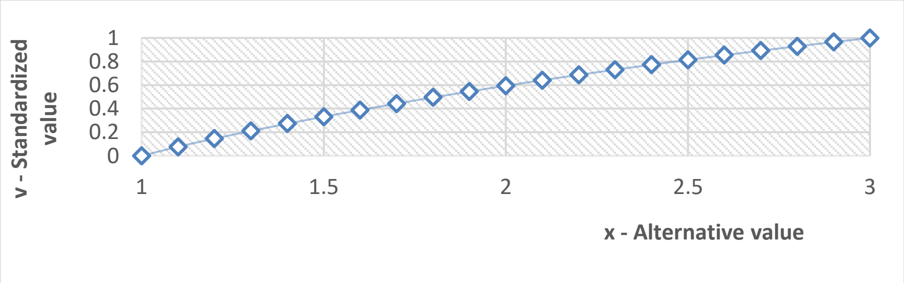
Table 23. Values of the alternatives of the link to historical events or traditions of public spaces.

Accessible for ambulances / firefighter

This indicator assesses the accessibility of a space to firefighters or ambulances. This indicator measures their ability of responding to the event on a short period regarding the accessibility to emergency response teams. In the case of historic areas, streets tend to be very narrow, so accessibility in case of an emergency is an important consideration. Hence, the indicator is if the space is accessible for firefighters, in case of a fire (more frequent during hotter periods) or the need to evacuate a person victim of a heat stroke or similar health problems caused by heat wave conditions by ambulance (Sobre et al. 2003; Anderson and Bell 2011).

As this is a coping capacity indicator, is therefore evaluated in negative (lack of), therefore the maximum value (1) is given to the alternative that has less coping capacity. After an analysis of the regulations in different regions, is concluded that firefighters need more area to manoeuvre than ambulances, therefore the alternatives are set as good accessibility if its accessible for firefighters, medium if is only accessible for ambulances, and none if is not accessible by neither. Hence, no accessibility will have the lower value (0) and good the maximum (1).

The following value function in Figure 36 represents the value of each alternative:



Xmin	1
Xmax	3
P	0.95
K	3
C	4

Figure 36. Shape, tendency and minimum and maximum values for accessibility of public space.

The following Table 24 shows the value assigned to each alternative:

Accessibility for ambulances or firefighters (according to local regulations)	VALUES
Good	0
Bad	0.7
None	1

Table 24. Values for the accessibility of public space.

The following table summarises the values for each alternative of the indicators regarding the vulnerability of the buildings.

INDICATOR		Alternatives and value		
1.2.1	**Albedo**	**Albedo of the space**		**VALUES**
		high	> 0.6	0.00
		medium	0.25 to 0.6	0.70
		low	< 0.25	1.00
1.2.2	**NDVI**	**Normalized Difference Vegetation Index**		**VALUES**
		high	> 0.5	0.00
		medium	0.2 to 0.5	0.35
		low	< 0.2	1
1.2.3	**SVF**	**Sky view Factor**		**VALUES**
		Very high	> 0.65	0
		high	0.5 to 0.65	0.2
		medium	0.35 to 0.5	0.8
		low	< 0.35	1
1.3.1	**Solar radiation**	**Shadow fraction**		**VALUES**
		very low	<0.2	0.00
		low	0.2 to 0.4	0.2
		medium	0.4 to 0.7	0.8
		high	0.7 to 1	1.00
1.3.2	**Air pollution**	**Air pollution (near surface ozone)**		**VALUES**
		very low	< 140 µg/m^3	0.00
		low	140 to 180 µg/m^3	0.32
		medium	180 µg/m3 to 240 µg/m^3	0.66
		high	> 240 µg/m^3	1.00
1.4.1	**Relevance to life (GF commercial activities on buildings)**	**GF commercial activities on buildings per 100m street / square**		**VALUES**
		low	Less than 5	0.00
		medium	Between 5 and 15	0.57
		high	More than 15	1.00
1.5.1	**Linked to historical events or traditions**	**Space linked to Historical events or traditions**		**VALUES**
		No		0
		Yes		1
2.1.1	**Accessible for ambulances / firefighter**	**Accessibility for ambulances or firefighters (according to local regulations)**		**VALUES**
		good		0
		bad		0,7
		None		1

Table 25. Summary of the values for each alternative of indicators regarding the vulnerability of public space.

Weights assignment for the indicators and criteria

The calculation for the weight of the indicators (γ) and the weight of the criteria (β) should be calculated next, before calculating the weight for the requirements (α) as the last step. The weight for the criteria and indicators are assigned by the pair comparison of the elements in the same level and in the same branch of the requirement tree. Therefore, the value of each indicator is calculated in according to the rest of the indicators belonging to the same criteria, and the criterion weight is calculated according to the criteria belonging to the same requirement.

For this process of weight assignment, as explained on chapter 2, AHP process was used to stablish the relative importance of each branch of the tree. The opinion of the panel of experts that evaluated the value of each indicator was used for the adjustment of the weights.

Weight of the sensitivity indicator for buildings

The sensitivity of the buildings, as set in the beginning of this chapter, is divided between 5 criteria, environmental sensitivity, social sensitivity, physical sensitivity, economic sensitivity and cultural sensitivity.

For the environmental sensitivity criteria, two indicators were defined, solar radiation and acoustic pollution. These two indicators were weighted by the panel of experts following the pair-wise comparison matrix shown in Table 26. As is a 2x2 matrix, there is no possible incoherence; hence, the consistency ratio will be always 0.

	Solar radiation	Acoustic pollution	Weight	Consistency
Solar radiation	1.00	3.20	0.76	
Acoustic pollution	0.20	1.00	0.24	0.00

Table 26. Pair wise comparison of the indicators of the environmental sensitivity criteria for buildings.

The social sensitivity criteria is composed in this case by three indicators, population density, date of construction of the building regarding its thermal behaviour and the percentage of vulnerable population residing in the building. The experts considered the vulnerable population the most relevant, followed by the date of construction and last the population density, as shown in Table 27.

	Vulnerable population	Date of construction	Population density	Weight	Consistency
Vulnerable population	1.00	3.20	1.00	0.45	
Date of construction	0.33	1.00	2.40	0.30	0.34
Population density	1.00	0.50	1.00	0.25	

Table 27. Pair wise comparison of the indicators of the social sensitivity criteria for buildings.

The physical sensitivity criteria, as the environmental one, is composed of two indicators, date of construction related to the degradation of materials and state of conservation. The panel of experts gave this two indicators almost equal weights, as shown in Table 28.

	Date of construction	State of conservation	Weight	
Date of construction	1.00	0.90	0.47	Consistency
State of conservation	1.11	1.00	0.53	0

Table 28. Pair wise comparison of the indicators of the physical sensitivity criteria for buildings.

As for the economic and cultural value criteria, they both are only composed of one branch with one indicator, and, hence, are weighted 1 each.

		Weight
Economic criteria	Primary use	1

Table 29. Weight of the economic sensitivity criteria indicators for buildings.

		Weight
Cultural value criteria	Link to historical events / traditions	1

Table 30. Weight of the cultural value sensitivity criteria indicators for buildings.

Weight of the coping capacity indicator for buildings

The coping capacity of buildings is divided between two criteria that has one indicator branch each; therefore, both indicators are weighted 1 as for the last two criteria in the sensitivity of buildings.

		Weight
Accessibility	Existence of elevator	1

Table 31. Weight of the accessibility criteria indicators.

		Weight
Cultural value	Level of protection	1

Table 32. Weight of the cultural value criteria indicators in coping capacity.

Weight of the criteria for buildings

As for the weight of indicators composing the criteria, a decision matrix was developed for the weighting and comparison of the criteria belonging to the same requirement blanch. In the case of buildings, this is the sensitivity requirement and the coping capacity requirement.

The sensitivity requirement is composed of 5 criteria, environmental, social, physical, economic and cultural sensitivity. This was evaluated by the same panel of experts achieving the following results shown on the pair comparison matrix in Table 38 .

	Environmental	Social	Physical	Economic	Cultural value	Weight	
Environmental	1.00	3.20	1.87	1.00	1.20	0.29	Consistency
Social	0.33	1.00	1.00	7.10	5.05	0.27	0.96
Physical	0.50	1.00	1.00	3.12	4.96	0.22	
Economic	1.00	0.14	0.33	1.00	4.80	0.15	
Cultural value	1.00	0.20	0.20	0.20	1.00	0.08	

Table 33. Pair-wise comparison of the criteria belonging to the sensitivity requirement for buildings.

For the coping capacity of buildings composed of the accessibility and cultural value criteria, the panel of experts weighted them almost equally, giving a slight edge to the cultural value one.

	Accessibility	Cultural value	Weight	
Accessibility	1.00	0.80	0.44	Consistency
Cultural value	1.11	1.00	0.56	0

Table 34. Pair-wise comparison of the criteria belonging to the coping capacity requirement for buildings.

Weight of the sensitivity indicator for public space

The sensitivity of public spaces is divided between three criteria, physical sensitivity, environmental and socio-cultural sensitivity. Each of this criteria gather seven indicators among them that are weighted as follows.

For the physical sensitivity criteria, the three indicators that compose it, albedo, NDVI and SVF are weighted almost equally as seen in Table 35.

	Albedo	NDVI	SVF	Weight	
Albedo	1.00	1.05	1.10	0.35	Consistency
NDVI	0.95	1.00	1	0.33	0
SVF	0.91	1.00	1.00	0.32	

Table 35. Pair wise comparison of the physical sensitivity indicators for public spaces.

In the case of the environmental criteria, composed by the indicators for solar radiation and air pollution, the panel of experts weight them given much more importance to solar radiation, as shown on Table 36 .

	Shadow fraction	Air pollution (near surface ozone)	Weight	
Shadow fraction	1.00	2	0.67	Consistency
Air pollution (near surface ozone)	0.5	1.00	0.33	0

Table 36. Pair wise comparison of the environmental criteria indicators for public space.

In the case of the socio-cultural criteria, the two indicators relevance (GF commercial activities on buildings) and the link of the space to historical events or traditions, were evaluated with almost similar weights by the panel of experts, giving a small more relevance to the second one (Table 37).

	Relevance (GF commercial activities on buildings)	Linked to historical events or traditions	Weight	
Relevance (GF commercial activities on buildings)	1.00	0.85	0.46	Consistency
Linked to historical events or traditions	1.18	1.00	0.54	0

Table 37. Pair wise comparison of the socio-cultural criteria for public spaces.

Weight of the coping capacity indicator for public space

The coping capacity indicators for public space, as seen before on this chapter, is only composed by one criteria and one indicator, being not necessary an evaluation, as the weight is 1.

		Weight
Accessibility of the urban grid	Accessible for ambulances/firefighters	1

Table 38. Weight of the accessibility indicator for coping capacity of public spaces.

Weight of the criteria for public space

As for the weight of the criteria for buildings, a decision matrix was developed for the weighting and comparison of the criteria belonging to the same requirement blanch. In the case of public space, this is divided between the sensitivity requirement and the coping capacity requirement.

The sensitivity requirement for public space is composed of 3 criteria, physical, social, and socio-cultural. They are weighted almost equally, with a slight edge for physical sensitivity, achieving the following results shown on Table 39 the pair comparison matrix in by the evaluation of the panel of experts.

	Physical	Environmental	Socio-cultural	Weight	Consistency
Physical	1.00	1.10	1.20	0.36	0
Environmental	0.95	1.00	1.00	0.32	
Socio-cultural	0.91	1.00	1.00	0.31	

Table 39. Pair-wise comparison of the criteria belonging to the sensitivity requirement for public space.

In the case of the coping capacity of public space as there is only one criteria, it will have a value of 1:

	Weight
Accessibility of the urban grid	1

Table 40. Weight of the coping capacity requirement for public space.

Requirement weights

For the final vulnerability assessment of both buildings and public space, sensitivity and coping capacity were weighted in proportion of the amount of indicators composing each requirement, resulting in the following matrix for buildings:

	Sensitivity of buildings	Coping capacity of buildings	Weight	Consistency
Sensitivity of buildings	1.00	4.50	0.82	
Coping capacity of buildings	0.22	1.00	0.18	0

Table 41. Weight of the requirements for buildings.

In the case of public spaces, the matrix is as shown on Table 42.

	Sensitivity of public spaces	Coping capacity of public spaces	Weight	
Sensitivity of public spaces	1.00	**6.50**	**0.87**	**Consistency**
Coping capacity of public spaces	0.15	1.00	**0.13**	**0**

Table 42. Weight of the requirements for public spaces.

The following Table 43 shows the weighting coefficients for the buildings requirement tree, and Table 44 shows the one for public space:

Req	Criteria weight	Criteria	Indicator weight	Indicator	Class	Range	VALUES
Sensitivity	0.29	Environmental	0.76	Solar radiation	Shadow fraction		VALUES
					very low	<0.2	0.00
					low	0.2 to 0.4	0.20
					medium	0.4 to 0.7	0.60
					high	0.7 to 1	1.00
			0.24	Acoustic pollution	Environmental		VALUES
					low	< 50 dBA	0.00
					medium	50 dBA to 70dBA	0.54
					high	> 70 dBA	1.00
	0.27	Social sensitivity	0.25	Population density	Inhabitants per sqm of residential area in the building		VALUES
					Empty	0	0.00
					Low	< 0.02 habs/m2	0.26
					medium	0.02 to 0.05 habs/m2	0.61
					high	> 0.05 habs/m2	1.00
			0.30	Date of construction (thermal comfort)	Date of construction		VALUES
					> 2006		0.00
					1970 to 2006		0.40
					1920 to 1970		0.69
					XVI to 1920		0.56
					< XVI century		1.00
			0.45	% of vulnerable population	population older than 65 years of age		VALUES
					low	< 25%	0.00
					medium	25% to 40%	0.62
					high	> 40%	1.00
	0.22	Physical	0.47	Date of construction (linked to vulnerability of materials)	Date of construction		VALUES
					> 2006		0.00
					1970 to 2006		0.40
					1920 to 1970		0.69
					XVI to 1920		0.56
					< XVI century		1.00
			0.53	State of conservation	State of conservation		VALUES
					Good		0.00
					Fair		0.36
					Bad		0.77
					Very bad /ruin		1.00
	0.15	Economic	1	Primary use	Primary use		VALUES
					Residential		0.82
					Industrial		0.48
					Public use (social/cultural)		0.84
					Touristic		0.43
	0.08	Cultural value	1	Linked to historical events or traditions	Link to Historical events or traditions		VALUES
					Yes		1
					No		0
Coping capacity	0.44	Accessibility	1.00	Elevator	Presence of elevator		VALUES
					Yes		0
					No		1
	0.56	Cultural value	1.00	Level of protection	Protection level of the building		VALUES
					Very high	Monument	1.00
					high	Integral	0.81
					medium	Typological	0.59
					Low	Basic / ambient	0.28
					None	None	0.00

Table 43. Weights for the buildings requirement tree for vulnerability.

Req	Criteria weight	Criteria	Indicator weight	Indicator	Indicators		VALUES
Sensitivity	0.36	Physical	0.35	Albedo	Albedo of the space		VALUES
					High	> 0.6	0.00
					Medium	0.25 to 0.6	0.70
					Low	< 0.25	1.00
			0.33	NDVI	Normalized difference vegetation index		Values
					High	0.5 < x	0.00
					Medium	0.2 to 0.5	0.35
					Low	X < 0.2	1
			0.32	SVF	Sky view Factor		VALUES
					Very high	> 0.65	0
					High	0.5 to 0.65	0.2
					Medium	0.35 to 0.5	0.8
					Low	< 0.35	1
	0.33	Environmental	0.67	Solar radiation	Shadow fraction		VALUES
					Very low	<0.2	0.00
					Low	0.2 to 0.4	0.2
					Medium	0.4 to 0.7	0.8
					High	0.7 to 1	1.00
			0.33	Air pollution	Air pollution (near surface ozone)		VALUES
					Very low	< 140 µg/m^3	0.00
					Low	140 to 180 µg/m^3	0.32
					Medium	180 µg/m3 to 240 µg/m^3	0.66
					High	> 240 µg/m^3	1.00
	0.31	Socio-Cultural	0.46	Relevance to life (GF commercial activities on buildings)	GF commercial activities on buildings per 100m street / square		VALUES
					Low	Less than 5	0.00
					Medium	Between 5 and 15	0.57
					High	More than 15	1.00
			0.54	Linked to historical events or traditions	Space linked to Historical events or traditions		VALUES
					Yes		1
					No		0
Coping capacity	1	Accesibility of urban grid	1	Accesible for ambulances / firefighter	Accesibility for ambulances or firefighters (according to local regulations)		VALUES
					Good		0
					Bad		0.7
					None		1

Table 44. Weights of the public spaces requirement tree.

3.2.3 Replicability. Adaptation to data availability.

The part of the methodology developed until this point in this chapter requires a relevant amount of data to feed the different indicators that will not always be available depending on the area under assessment. The application of the methodology in the two case studies in chapters 4 and 5 will show that, even if in at ideal scenario the use of all indicators would provide the best results, the methodology has to be flexible and adaptable to data limitations to prove replicable.

For replicability, the decision tree needs to be able to adapt to different number of indicators in a balanced way. For this, the following is proposed and applied in both case studies. Following the weights and values provided by the evaluation by the panel of experts, they are kept in the same proportions when some indicators or criteria are eliminated. This means that the missing indicators weight is given to the rest of the indicators within the criteria maintaining the proportions provided by the pair-wise comparison matrix, and the same is done when a criteria is eliminated, sharing the weight of that criteria among the rest maintaining the proportions between them.

As an example, the indicators for acoustic pollution, accessibility and the link to historical links or traditions are eliminated from the buildings decision tree. When the indicator for acoustic pollution is eliminated from the environmental criteria, being one of two, the missing one becomes the only one and therefore has 100% of the weight within the criteria. The same thing happens when the criteria for accessibility disappears from the coping capacity, the other one, cultural value, gathers now 100% of the weight within that requirement.

In the case of the cultural value criteria, when is eliminated its weight it is shared by the rest of the criteria composing the sensitivity maintaining the proportions. This is, as cultural value has 15% of the weights, the remaining criteria will pass from 85% to the 100% of the weight in the same proportions the already have between them. The original matrix shown on Table 33 will change to this:

	Environmental	Social	Physical	Economic	Weight	Consistency
Environmental	1.00	3.20	1.87	1.00	0.37	0.96
Social	0.33	1.00	1.00	7.10	0.28	
Physical	0.50	1.00	1.00	3.12	0.22	
Economic	1.00	0.14	0.33	1.00	0.13	

Table 45. Example of weight adaptation for data limitations.

Req	Criteria		Indicators				
Sensitivity	0.37	Environmental	1	Solar radiation	**Shadow fraction**		**VALUES**
					very low	<0.2	0.00
					low	0.2-0.4	0.20
					medium	0.4-0.7	0.60
					high	0.7-1	1.00
	0.28	Social sensitivity	0.25	Population density	**Inhabitants per sqm of residential area in the building**		**VALUES**
					Empty	0	0.00
					Low	x<0.02 habs/m2	0.26
					medium	0.02 < x < 0.05 habs/m2	0.61
					high	0.05 < x habs/m2	1.00
			0.30	Date of construction (thermal comfort)	**Date of construction**		**VALUES**
					>2006		0.00
					1970<x2006		0.40
					1920<x<1970		0.69
					XVI<x<1920		0.56
					<XVI century		1.00
			0.45	% of vulnerable population	**population older than 65 years of age**		**VALUES**
					low	x < 25%	0.00
					medium	25% < x < 40%	0.62
					high	40% < x	1.00
	0.22	Physical	0.47	Date of construction (linked to vulnerability of materials)	**Date of construction**		**VALUES**
					>2006		0.00
					1920<x<2006		0.40
					1850<x<1920		0.69
					XVI<x<1850		0.56
					<XVI century		1.00
			0.53	State of conservation	**State of conservation**		**VALUES**
					Good		0.00
					Fair		0.36
					Bad		0.77
					Very bad /ruin		1.00
	0.13	Economic	1	Primary use	**Primary use**		**VALUES**
					Residential		0.82
					Industrial		0.48
					Public use (social/cultural)		0.84
					Touristic		0.43
CC	1	Cultural value	1.00	Level of protection	**Protection level of the building**		**VALUES**
					Very high	Monument	1.00
					high	Integral	0.81
					medium	Typological	0.59
					Low	Basic / ambient	0.28
					None	None	0.00

Table 46. Example of adaptation of weights to less indicators.

3.2.4 Tuning of alternatives

The last step to get a vulnerability index using MIVES, as explained in chapter 2, is to multiply the weights of the indicators by their criteria and their requirement. The result can be visualized in two ways, as a numerical value or as a value of the vulnerability index. The numerical value will be the result of the final weight of the values of each indicator, criteria and requirement for each element. The vulnerability index is given by adding the sensitivity index to the coping capacity index, as both are negative aspects, their adding will be positive. The higher number as a result, the more vulnerable the building or public space. Both this ways will be compared in the case studies to decide on the most accurate to achieve the best representativeness.

The two requirements of sensitivity and coping capacity are calculated separately, as an element can have very high sensitivity but have a high coping capacity, of vice versa. This way a more realistic picture of the situation is achieved.

For the vulnerability index calculation, the index for both sensitivity and coping capacity need to be ranked and different categories are created as a result, composed by the criteria and indicators and their corresponding weights.

Sensitivity will be divided into 5 categories and coping capacity into 3, as shown in the following lists, following the approach for a ranking system proposed by Kleinfelder (City of Cambridge 2015), that modifies the ICLEI system to a quantitative one.

Sensitivity index:

- **S0** $\leq$ 0.10
- 0.10 < **S1** $\leq$ 0.40
- 0.40 < **S2** $\leq$ 0.60
- 0.60 < **S3** $\leq$ 0.80
- 0.90 < **S4** $\leq$ 1.00

Coping capacity index:

- **CC0** $\leq$ 0.33
- 0.33 < **CC1** $\leq$ 0.75
- 0.75 < **CC2** $\leq$ 1.00

As shown on Table 47 vulnerability has different levels according to the sensitivity and coping capacity of the element, from V0 to V5.

		Sensitivity: low to high				
		S0	S1	S2	S3	S4
Lack of coping capacity: Low to high	CC1	V0	V1	V1	V2	V3
	CC2	V1	V2	V2	V3	V4
	CC3	V2	V3	V4	V5	V5

Table 47. Vulnerability levels.

3.2.5 Categorization of HUA

Categorization is a very relevant step in a risk assessment methodology when it comes to its replicability, as it provides confidence when achieving general knowledge on asset vulnerability on a macro-scale. This method helps to achieve an assessment of risk or vulnerability when fewer data is available, by creating representative categories of the elements with fewer indicators and then building the rest using sample elements of each category.

To achieve risk assessment with limited data availability, this categorization method is presented in the thesis as a proposal. This way, with a few more representative indicators as a base, via the creation of categories is possible to assess most of the elements in the area. This method will be tested in chapter 4 and its results compared to rate its accuracy.

For the analysis of a large and varied stock of buildings and public spaces such as an urban area, a statistical approach may be used, with the aim to describe all the assets using archetypes o sample assets. Sample assets refer to real elements of the area that include measured data, on the other hand, archetypes include estimated statistical data (Ballarini et al. 2011; Swan and Ugursal 2009). The methodology for the categorization of an area will be, therefore, a statistical distribution of the characteristics of both buildings and open spaces, starting from samples and then extrapolating these results to elements of the same category, thereby obtaining an overall vulnerability assessment for the historic area. With this goal in mind, the objective is to create a limited number of samples that are able to represent almost the entire building stock and public space of the historic urban area considering the limitations imposed by data availability. These categories should reflect the vulnerabilities of both buildings and public space to heat waves, considering their cultural value, use, social and constructive characteristics following the approach used for the development of the indicators. Furthermore, data should be as widely available as possible, in order to build a replicable model for different case studies (A Gandini et al. 2020)(Egusquiza et al. 2018). Hence, for the step of the generation of the categories, the characteristics of the urban area and the concentration of different values is very relevant.

This parameters will also depend on the specific characteristics of the historic are under assessment. All the parameters described above will result in a very large number of categories, therefore depending on the data availability and characteristics of the assessed area some of them will be discarded and the thresholds set, to achieve the right balance between relevance of the information, representativeness and number of categories.

For this, as is it important to consider the equilibrium between the amount of categories and their representativeness considering the relevance of the indicators, once the categories are developed, a minimum threshold is set to discard the less representative ones. Depending on the size and characteristics on homogeneity that the area presents, the threshold should be set between the 2% and 5% for the best results (Egusquiza et al. 2018).

In summary, the process for categorization is as follows:

1. Statistical overview of the historic area
2. Select the parameters to be used and stablish the ranges and thresholds for the different categories. The goal in this step is to achieve maximum representativeness with the minimum categories
3. Discard categories that do not achieve the minimum threshold for representation (between the 2% and 5%)
4. Categories are generated

When the categories are stablished, sample elements are selected to represent each category. Depending on the characteristics of the historic area and the data availability on different elements, the criteria for the selection can vary. Is important to consider representativeness when selectin sample elements, as the results will be extrapolated to the whole category, therefore the use of an statistical approach can help to discard the ones which have parameters outside of the range.

For the present study, the workflow is proposed as follows: the first step is the collection of information to feed a multiscale data model, which in turn provides a statistical overview of the historical area and feeds the sample building categorization process that composes the second step. The more complete information gathered during this process is basis for the last and third step of the vulnerability and risk assessment. All of this process will feed a multiscale data model based on GIS that will provide the visualization of the risk.

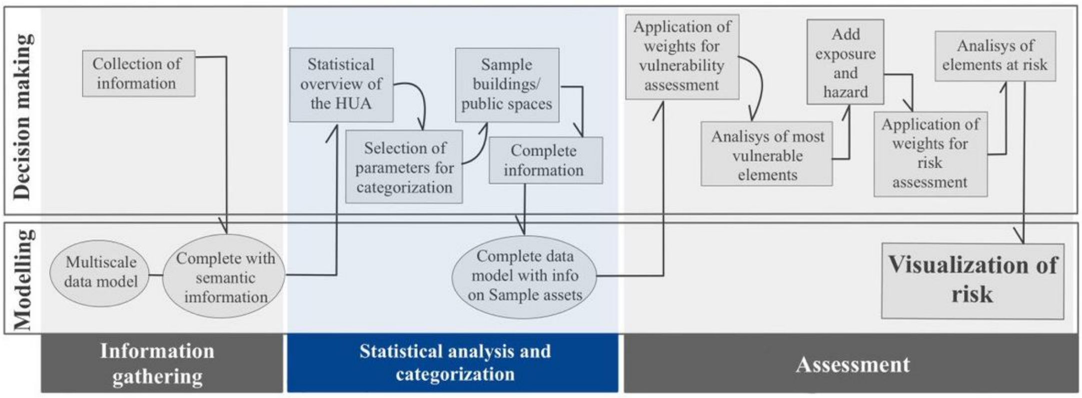


Figure 37. Workflow process from the collection of information to the visualization of risk.

Categorization of buildings

According to the above-mentioned requirements, for buildings, the categorization will be based on their following parameters selected from the main body of indicators than are considered replicable and that provide an overview of the vulnerability of the buildings.

- Solar radiation.
- Year of construction. Divided into construction periods that have similar construction techniques/materials, and consequently, the same vulnerability to heat waves.
- Use. For this category the buildings main use is considered, distinguishing between residential, industrial, public use and touristic use..
- Cultural value: The protection level of the buildings.
- Social sensitivity: population density is the main category in this area.

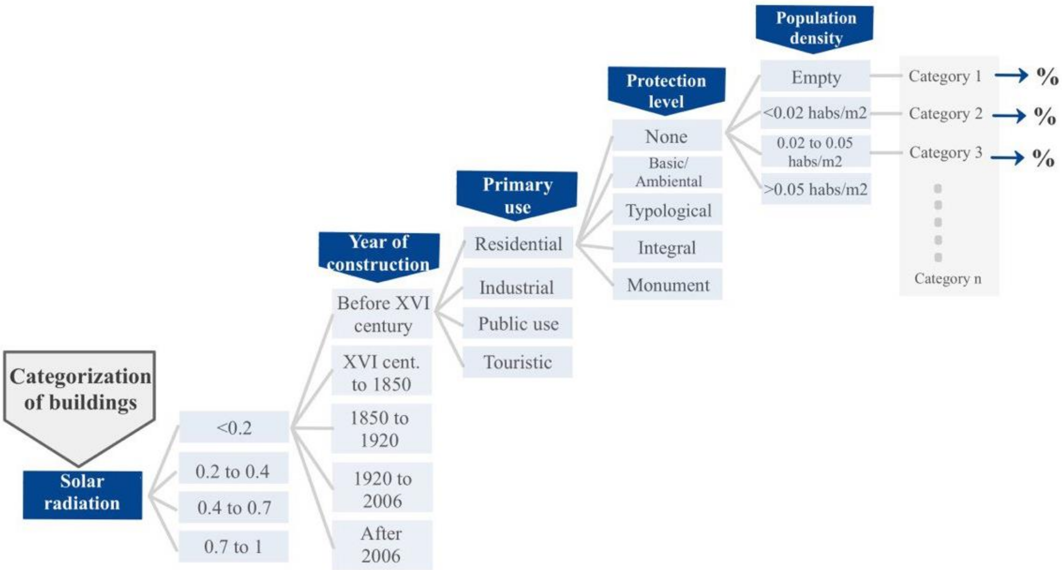


Figure 38. Example for the categorization process for buildings.

Categorization of urban space

For the categorization of public space, the following parameters were chosen following physical sensitivity and cultural value characteristics:

- Physical sensitivity: this main category for public space if created with three subdivisions, starting with the Sky View Factor to predict the possible street canyons, then adding NVDI levels to measure the amount of vegetation and adding solar radiation of the spaces as the last characteristic.
- Cultural value: for cultural value the relevance of the space for the live in the area is considered.

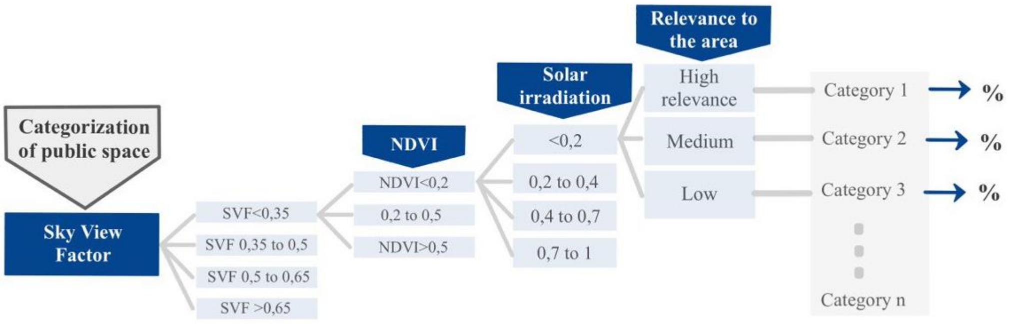


Figure 39. Example of the proposal for the categorization process for public space.

3.3 Risk assessment

As stated on the second chapter of the thesis, risk is the result of the interaction between the hazard, the exposure and the vulnerability of the assets, composed by the sensitivity and the coping capacity presented in the previous sections of this chapter. For the calculation of the risk, therefore, two other requirements are needed, exposure and hazard.

3.3.1 Heat wave characterization – Hazard and exposure indicators

Heat waves are one of the most threatening natural hazards that can adversely affect human health, ecosystems, infrastructure and urban areas (Zuo et al. 2015). Population in urban areas are very vulnerable to extremes in heat and relative humidity and heat wave events can have important consequences in human health and increase mortality rates. Numerous studies indicate that climate change is expected to aggravate heat wave events, becoming more frequent and increasing their duration and intensity. Although there is no standard definition of the heat wave, it can be referred as a period of consecutive days of abnormal high temperature. The WMO guidance on heat-health warning (WMO-No.1142) defines heatwaves as periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least two to three days and a discernible impact on human activities (World Meteorological Organization 2018; L. Zhao et al. 2018). Therefore, the main indicators to characterize heat waves are temperature and relative humidity (RH); with levels of RH defining if it is a dry heat wave or a humid heat wave (X. Chen et al. 2019).

These extreme heat events are becoming a growing concern for cities and urban areas, because high temperatures reached during heat waves are often exacerbated due to specific urban phenomenon called the urban heat island (UHI) effect (Li and Bou-Zeid 2013). UHI are the observed characteristic of urban areas to have higher temperatures than their surrounding rural areas (Gartland 2010). This is due to the way urban geometry and materials influence wind flow, energy absorption, and the ability of surfaces to emit long wave radiation back to space. On the one hand, a resting human body generates about 100 W of metabolic heat (in addition to any absorbed solar heating) and cannot dissipate heat if the ambient temperature is higher than the optimum body temperature (near 37 ºC). On the other hand, sweating, the main process by which the body transports away the environmental and metabolic heat loads, will become significantly less effective if the environmental relative humidity is high, resulting in heat accumulation in the body and increases in both morbidity and mortality. Other than the effects that heat waves have on the thermal comfort and human health, there is a significant impact on the degradation of historic materials, as described on chapter 2 and the development of indicators previously in this chapter.

Exposure

Exposure in the IPCC framework, as explained on the beginning of the thesis, is defined as "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected"(IPCC, 2014). Hence, it refers to the elements in the area affected by the hazard, it is possible for an asset to be exposed but not be vulnerable; yet, to be vulnerable it needs to be exposed to the event. In the case of heat waves, the exposure if all the assets belonging to the same area to the hazard is the same. Contrary to other hazards, such as floods or earthquakes, where the exposure to the hazard varies depending on the proximity to the source, heat waves are climatological conditions that affect an area at large. Therefore, the same conditions of exposure to the hazard affect all assets in the same area under the same heat wave characteristics. For this reason, the exposure requirement is considered weighted as 1 equally for all the elements under assessment, being therefore negligible.

	Weight
Accessibility of the urban grid	1

Table 48. Weight of the exposure requeriment.

Hazard characterization and indicators

As mentioned before heat waves are characterized using temperature and relative humidity (RH). The threshold for a HW varies depending on the location, and each country/region has its own definition depending on their specific climate. Basic characterization of a HW would need, therefore, as indicators, daily mean temperature and RH. As a further characterization of the intensity of the hazard and its possible implications for population and historic materials, other indicators must be considered (Brimblecombe, Grossi, and Harris 2011; E. Sesana et al. 2021). Additional variables that influence heat wave characterization are the ones that determine the fluctuations on temperature and RH in a daily basis, such as daily RH cycle shocks, humidity cycles that surpass 75% RH, and thermal shocks. One other parameter that can have an important determination in characterization of the intensity and effects of HW is the number of daily sun hours that considers the amount of solar radiation that an area has received in a day.

All of these indicators characterize the risk of HW in historic areas due to their effect on the weathering of traditional construction materials.

Considering all of this indicators, the final requirements tree, including the hazard and exposure requirement is presented in Figure 40 for buildings and in Figure 41 for public spaces. The final tree contains therefore, 10 criteria and 16 indicators for buildings and 7 criteria and 13 indicators for public spaces.

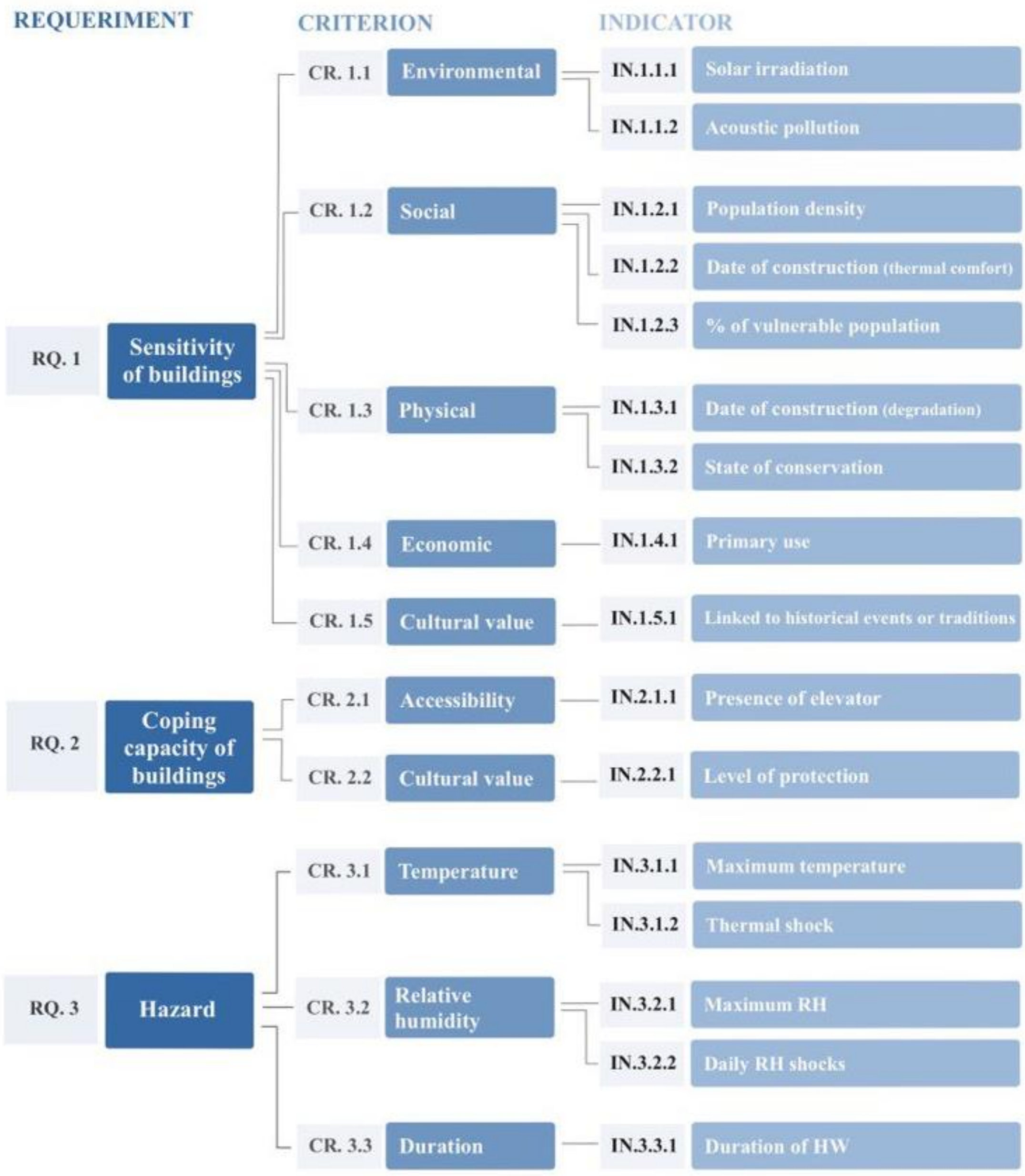


Figure 40. Final requirement tree for buildings.

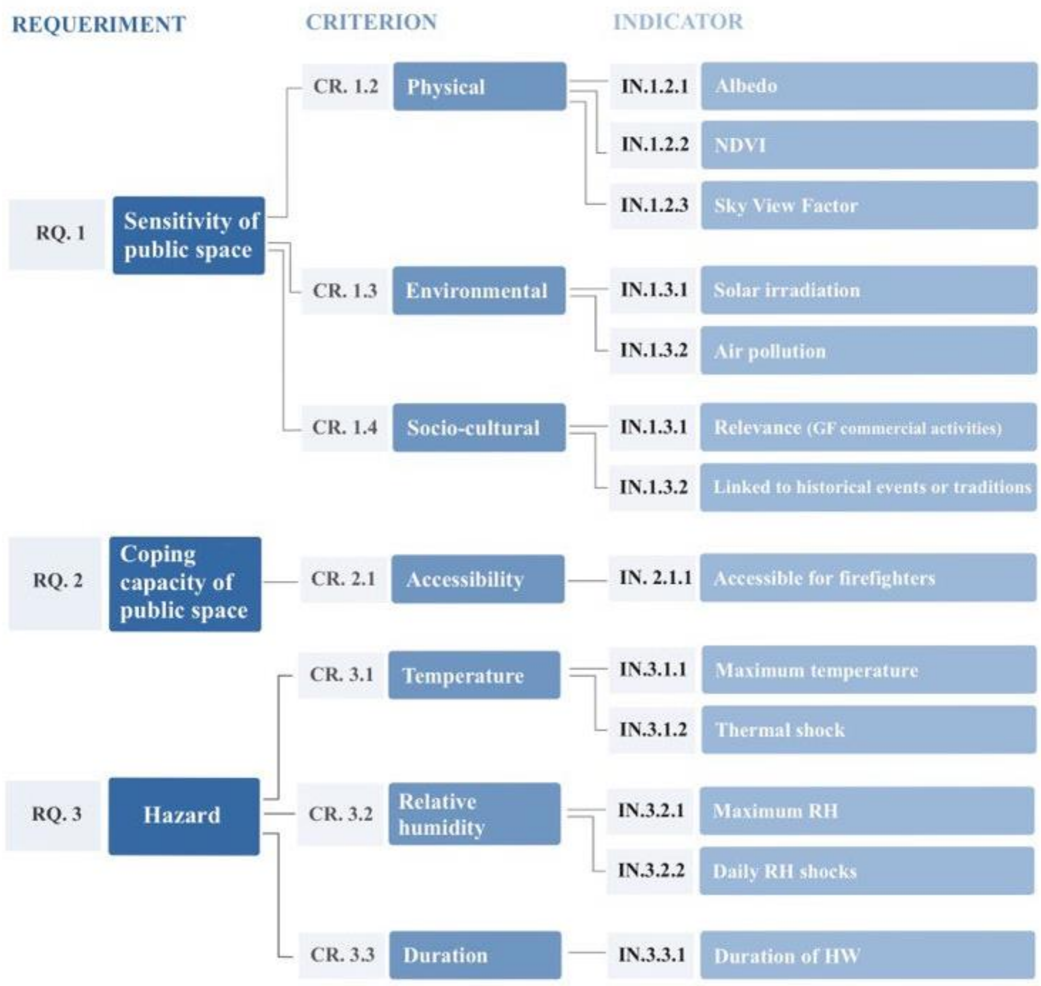


Figure 41. Final requirement tree for public spaces.

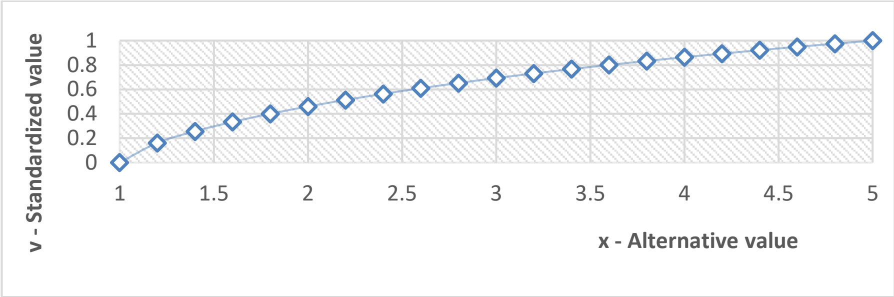
The indicators for hazard as shown on both Figure 40 and Figure 41 are divided into three criteria, temperature, relative humidity and duration.

Temperature criteria

The temperature criteria for the characterization of heat waves is divided between two indicators, maximum temperature and thermal shock or variation.

The first one is the maximum temperature, as heat waves are only considered as such when lasting more than 3 days the data will be the mean maximum temperature of all days surpassing the heat wave threshold. The values considered in this case vary depending on the region being assessed, as the emergency thresholds for each level are set by the regional regulations. Here the ones for Bilbao are used, being a heat wave only when surpassing 30ºC (Díaz, Carmona, and Linares 2015), more than 36ºC yellow alert, over 38ºC orange alert, and over 40ºC red alert.

Following this and the experts’ evaluation, the value function in Figure 42 represents the value of each alternative.



Xmin	1
Xmax	5
P	0.7
K	2
C	7

Figure 42. Shape, tendency and minimum and maximum values for temperature.

The following table shows the value assigned to each alternative:

Maximum temperature		VALUES
No Heat Wave	less than 30ºC	0.00
Low	30 to 36ºC	0.54
Medium	36 to 38 ºC	0.76
High	38 to 40 ºC	0.90
Extreme	> 40ºC	1.00

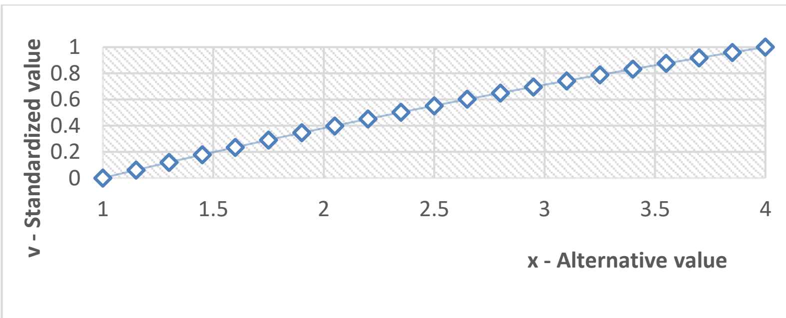
Table 49. Values of the alternatives for temperature.

In the case of thermal shocks, this are used to describe the difference of temperature between the minimum (usually at night) and the maximum day time temperature. This can be correlated to the urban heat island effect, as a lower difference between night and day temperatures during a heat wave are characteristic of large urban areas. The higher value therefore will be assigned to the lower difference between day and night time temperatures following the formula on Equation 15.

$$Thermal\ shock: T_{max} - T_{min} = X°C$$

Equation 15. formula for thermal shock calculation.

Following this and the experts' evaluation, the value function in Figure 43 represents the value of each alternative.



Xmin	1
Xmax	5
P	0.7
K	2
C	7

Figure 43. Shape, tendency and minimum and maximum values for thermal shock.

The following table shows the value assigned to each alternative:

Thermal shock		VALUES
Very high	> 20ºC	0.00
High	15 to 20ºC	0.18
Medium	10 to 15ºC	0.53
Low	7 to 10ºC	1.00

Table 50. Value of the alternatives for thermal shock.

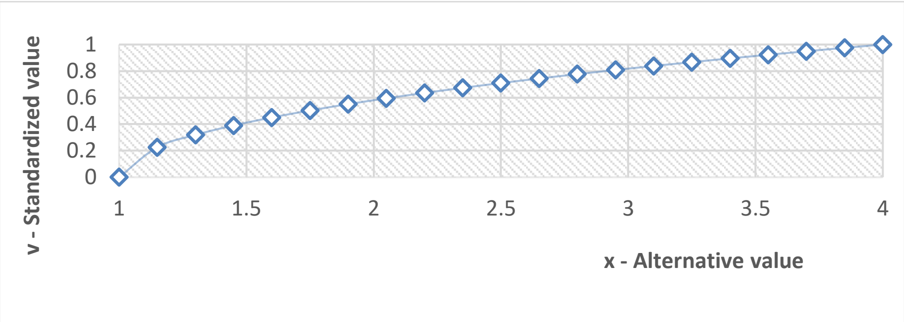
Relative humidity criteria

The relative humidity criteria for the characterization of heat waves is divided between two indicators, maximum relative humidity (%) and daily RH shocks.

The relative humidity affects the characterization of heat waves as dry or humid heat waves (Russo, Sillmann, and Sterl 2017; Guerreiro et al. 2018). As explained in chapter 2 and the introduction of this section, higher relative humidity under heat wave conditions can result in higher mortality rates and a reduced thermal comfort, as it reduces the capacity of the body to regulate temperature.

The alternatives for this indicator will be less than 40% considered as the lower one (valued 0), and over 85% as an extreme RH (valued 1).

Following this and the experts' evaluation, the value function in Figure 44 represents the value of each alternative.



Xmin	1
Xmax	4
P	1
K	0.2
C	1

Figure 44. Shape, tendency and minimum and maximum values for relative humidity.

The following table shows the value assigned to each alternative:

Relative humidity (%)		VALUES
Low	Less than 40%	0.00
Medium	From 40 to 60%	0.42
High	From 60 to 85	0.72
Extreme	Higher than 85%	1.00

Table 51. Value of the alternatives for relative humidity.

In the case of relative humidity shocks, this are very relevant to determine the impact on materials, are frecuent and extreme humidity variations are shown to accelerate the degradation of traditional materials (Brimblecombe, Grossi, and Harris 2011; E. Sesana et al. 2021). Humidity shocks are defined as variations on relative humidity of more than 25% (Equation 16), being this indicator the amount of humidity shocks happening during a day under heat wave conditions.

$$RH\ shocks: (RH_n - RH_{n+1}) > 25\%$$

Equation 16. Formula for relative humidity shocks (RH shocks).

The alternatives in this case are set as 1 shock or less being the lower (valued 0), 2 to 4 being medium, and more than 5 the highest (valued 1).

Following this and the experts' evaluation, the value function is a linear one, with Table 52 showing the value assigned to each alternative:

	RH shocks	VALUES
Low	1 or less	0.00
Medium	2 to 4	0.50
High	More than 5	1.00

Table 52. Value of the alternatives for RH shocks.

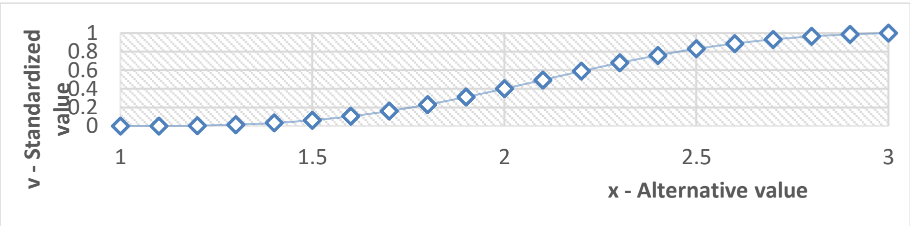
Duration criteria

This criterion is composed by a single indicator measuring the duration of the heat waves in days. This is the amount of consecutive days when the maximum temperature exceeds the threshold by the heat wave definition.

As mentioned in the introduction to this section, a heat wave is characterized in its core as several days with maximum temperatures exciding a threshold set depending the region and climate. This duration varies depending on the definition, but as the WMO defines a minimum a duration of at least two to three days, and three days is the threshold set by both of the case studies, it was used to define the alternatives for this methodology.

The alternatives, hence, are less than 2 days the minimum value of 0, and more than 5 consecutive days having the maximum of 1.

Following this and the experts' evaluation, the value function in Figure 45 represents the value of each alternative.



Xmin	1
Xmax	3
P	3
K	0.5
C	1

Figure 45. Shape, tendency and minimum and maximum values for duration of the heat wave.

The following table shows the value assigned to each alternative:

Duration in days		VALUES
Low	1 to 2 days	0.00
Medium	3 to 4 days	0.40
High	More than 5 days	1.00
Low	1 to 2 days	0.00

Table 53. Value of the alternatives for duration.

Weight assignment for hazard criteria and indicators

As for the vulnerability assessment, the same process of using Analytic Hierarchy Process (AHP) was used for stablishing the relative importance of the hazard criteria and indicators. This process includes the hazard as the third requirement in the decision tree, obtaining both the building and public spaces risk calculation.

Weight of the hazard indicators

As previously don both for sensitivity and coping capacity indicators, a reciprocal matrix for pair-wise comparison is used to obtain the priorities and check their consistency. The hazard requirement is composed by three criteria, temperature, humidity and duration.

Temperature criteria is divided into two indicators, maximum temperature and thermal shocks, weighted as follows:

	Maximum temperature	Thermal shocks	Weight	
Maximum temperature	1.00	2.75	0.73	Consistency
Thermal shocks	1.18	1.00	0.27	0

Table 54. Pair wise comparison of thetemperature criteria.

As for the relative humidity criteria, is also composed of two indicators, maximum relative humidity and thermal shocks. In this case also the maximum RH was weighted higher than the RH shocks as shown in Table 55.

	Maximum relative humidity	RH shocks	Weight	
Maximum relative humidity	1.00	2.05	0.68	Consistency
RH shocks	1.18	1.00	0.32	0

Table 55. Pair wise comparison of relative humidity indicators.

Finally, in the case of the duration criteria, as it is only composed of one indicator, is will have the full weight of 1.

Weight of the criteria for hazard

As previously the weight of the criteria, composing the hazard requirement is achieved by pair-wise comparison. This requirement contains three criteria, temperature, relative humidity and duration of the heat wave.

The following table shows the matrix comparing the weights of the three criteria:

	Temperature	Relative humidity	Duration	Weight	
Temperature	1.00	3.20	2.50	0.58	Consistency
Relative humidity	0.31	1.00	0.90	0.19	0
Duration	0.40	1.11	1.00	0.22	

Table 56. Pair-wise comparison of the hazard criteria.

Temperature has, therefore, the higher weight compared to relative humidity and duration, that are mostly equally weighted.

3.3.2 Final requirement weight and alternatives

As a new requirement has been introduced, a new index for risk has to be calculated.

Requirement weights

For the final vulnerability assessment of both buildings and public space, sensitivity and coping capacity were weighted in proportion of the amount of indicators composing each requirement, resulting in the following matrix for buildings:

	Sensitivity of buildings	Coping capacity of buildings	Weight	
Sensitivity of buildings	1.00	4.50	0.82	Consistency
Coping capacity of buildings	0.22	1.00	0.18	0

Table 57. Weight of the requirements for vulnerability of buildings.

In the case of public spaces the matrix is as shown on Table 42.

	Sensitivity of public spaces	Coping capacity of public spaces	Weight	
Sensitivity of public spaces	1.00	6.50	0.87	Consistency
Coping capacity of public spaces	0.15	1.00	0.13	0

Table 58. Weight of the requirements for vulnerability of public spaces.

The weight between hazard and vulnerability will be divided equally, therefore in the case of buildings the matrix would be as follows:

	Hazard	Sensitivity	Coping capacity	Weight	
Hazard	1.00	1.00	0.50	0.50	Consistency
Sensitivity	1.00	1.00	1.00	0.41	0
Coping capacity	2.00	1.00	1.00	0.09	

Table 59. Weight of the final requeriments for building risk.

And for public spaces the weight of the requirements will be as shown on table .

	Hazard	Sensitivity	Coping capacity	Weight	
Hazard	1.00	1.00	0.50	0.50	Consistency
Sensitivity	1.00	1.00	1.00	0.43	0
Coping capacity	2.00	1.00	1.00	0.07	

Table 60. Weight of the final requeriments for public space.

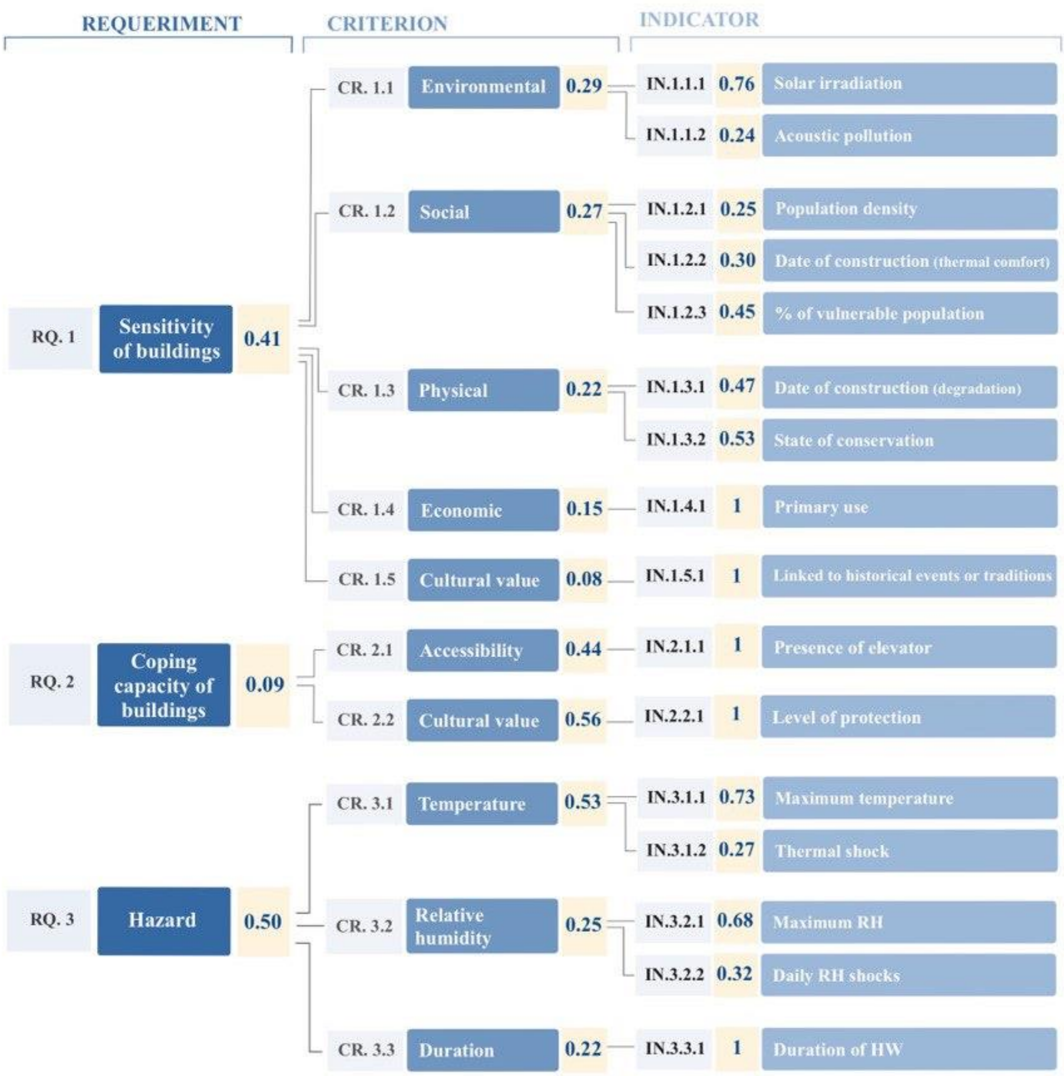


Figure 46. Final requirement tree for buildings with weights.

Figure 46 shows the final selection of indicators and their weights for buildings, while Figure 47 shows the ones for public spaces.

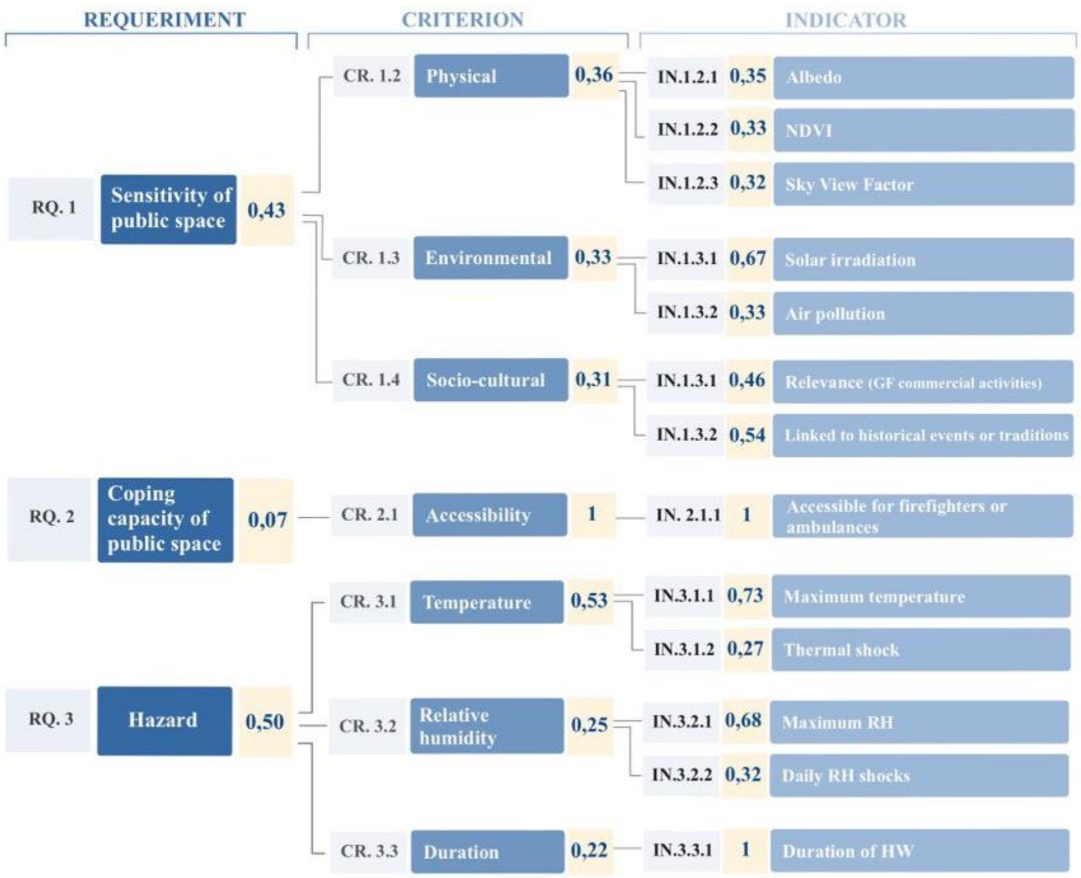


Figure 47. Final requirement tree for public spaces with weights.

Alternatives

As described for the vulnerability assessment, to perform the evaluation of alternatives the value of the indicator is multiplied by the criteria weight and finally the weight of the requirement. The weight of the indicator is given by the value function in accordance to its weight. The risk index is the sum of the values of the three requirement, hazard, sensitivity and coping capacity.

As with vulnerability, the risk will be provided two ways, as a numerical value or with the use of a risk index.

For the index, as for vulnerability, the levels for the hazard need to be stablished, following three ranges:

- **H0** ≤ 0.33
- 0.33 < **H1** ≤ 0.75
- 0.75 < **H2** ≤ 1.00

As shown on Table 61 risk has different levels according to the hazard range and vulnerability of the element, from V0 to V5.

		Vulnerability: low to high				
		V0	V1	V2	V3	V4
Hazard: Low to high	H1	R0	R1	R1	R2	R3
	H2	R0	R2	R2	R3	R4
	H3	R1	R3	R4	R5	R5

Table 61. Risk levels.

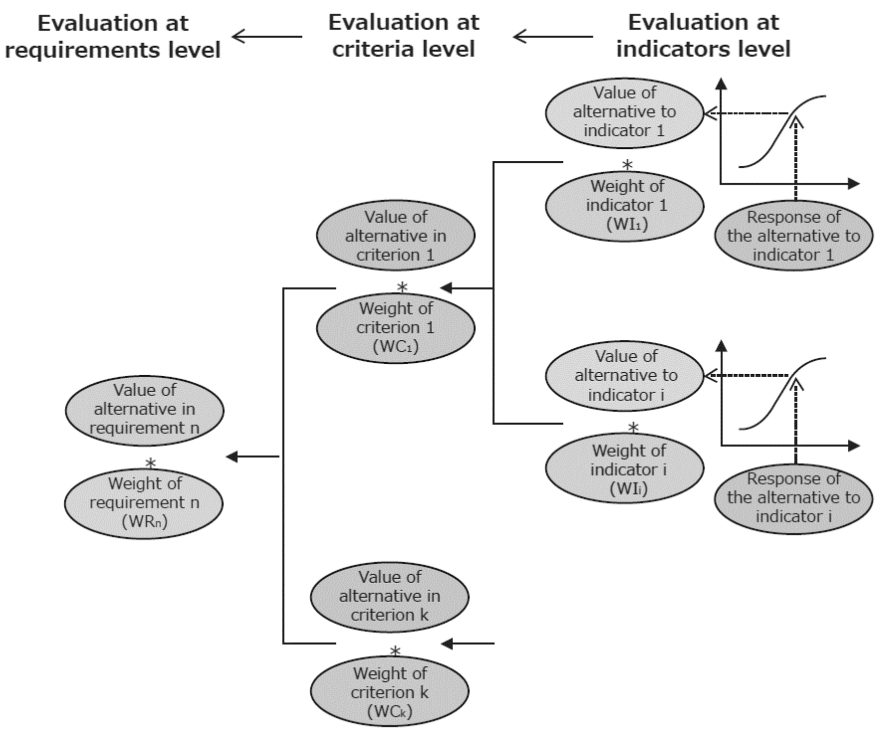


Figure 48. Alternative aqssessment. Adapted from (Viñolas, Aguado, and Josa 2011).

3.3.3 MIVES and categorization

As previously developed on the categorization section of this chapter, the characterization for both buildings and public space is performed for the vulnerability assessment by a selection of parameters. Once all the data is gathered and introduced the sample elements are selected, for both buildings and public space. As a next step, MIVES will be applied to the sample buildings and values attached to the indicators. Lastly, the hazard indicators included in the methodology will be completed to assess the risk of the sample elements.

The analysis of the indicators will be done using percentages to consider the overall weight of each indicator and advance some considerations.

The following Table 62 shows the assessment of all the indicators for sample buildings at criteria level, expressed in percentages, while the Table 63 does the same with the indicators for public space.

		Weight	Criteria	Weight	Indicator		Weight over criteria	Overall weight
Sensitivity	41%	29%	Environmental	76%	Solar radiation	Solar radiation	19%	8.17%
				24%	Acoustic pollution	Environmental	6%	2.58%
		27%	Social sensitivity	25%	Population density	Inhabitants per sqm of residential area in the building	8%	3.44%
				30%	Date of construction (thermal comfort)	Date of construction	9.6%	4.13%
				45%	% of vulnerable population	population older than 65 years of age	14.4%	6.19%
		22%	Physical	47%	Date of construction (linked to vulnerability of materials)	Date of construction	8.93%	3.84%
				53%	State of conservation	State of conservation	10.07 %	4.33%
		15%	Economic	100%	Primary use	Primary use	13%	5.59%
		8%	Cultural value	100%	Linked to historical events or traditions	Link to Historical events or traditions	15%	6.45%
CC	9%	44%	Accessibility	100%	Elevator	Presence of elevator	44%	3.08%
		56%	Cultural value	100%	Level of protection	Protection level of the building	56%	3.92%
Hazard	50%	53%	Temperature	73%	Maximum temperature	Max temperature	38.69 %	19.34%
				27%	Thermal shock	Thermal Shock: (Tmax-Tmin)>X°C -Intensity of UHI	14.31 %	7.15%
		25%	Relative humidity	68%	Maximum RH	Maximum RH	17%	8.5%
				32%	RH shocks	Daily RH shocks (RH(n)-RH(n+1)) > 25%	8%	4%
		22%	Duration	100%	Duration (days)	Duration (number of consecutives days over temperature threshold)	22%	11%

Table 62. Assessment of the building indicators at criteria level expressed in percentage.

		Weight	Criteria	Weight	Indicators		Weight over criteria	Overall weight
Sensitivity	43 %	36%	Physical	35%	Albedo	Albedo of the space	12.6%	5.42%
				33%	NDVI	Normalized Difference Vegetation Index	11.88%	5.11%
				32%	SVF	Sky view Factor	11.52%	4.95%
		33%	Environmental	67%	Solar radiation	Shadow fraction	22.11%	9.50%
				33%	Air pollution	Air pollution (near surface ozone)	10.89%	4.68%
		31%	Socio-Cultural	46%	Relevance to life (GF commercial activities on buildings)	GF commercial activities on buildings per 100m street / square	14.26%	6.13%
				54%	Linked to historical events or traditions	Space linked to Historical events or traditions	16.74%	7.20%
CC	7 %	100%	Accessibility of urban grid	1	Accessible for ambulances / firefighter	Accessibility for ambulances or firefighters (according to local regulations)	100%	7%
Hazard	50 %	53%	Temperature	73%	Maximum temperature	Max temperature	38.69%	19.34 %
				27%	Thermal shock	Thermal Shock: (Tmax-Tmin)>XºC - Intensity of UHI	14.31%	7.15%
		25%	Relative humidity	68%	Maximum RH	Maximum RH	17%	8.5%
				32%	RH shocks	Daily RH shocks (RH(n)-RH(n+1)) > 25%	8%	4%
		22%	Duration	100%	Duration (days)	Duration (number of consecutives days over temperature threshold)	22%	11%

Table 63. Assessment of the public space indicators at criteria level expressed in percentage.

In the case of the buildings, the selected indicators for the categorization, namely year of construction, use, link to historical events and population density, represent 54,3% of the sensitivity requirement while protection level represents 56% of the coping capacity.

When considering the categorization indicators for public spaces, the selected ones being SVF, NDVI, relevance to the area and its link to communal memories or traditions, the represent the 54,4% of the sensitivity requirement.

3.4 Data modelling and management

A multiscale data model for the management of information is necessary as part of the methodological approach to support the decision making process and provide proper visualization of the results.

As described in the methodological part of this thesis, a data model with both geometric and semantic data is necessary. As a first step the basic geometry of the historic area is needed, of both buildings and public spaces, at a reasonable level of detail that supports the calculation of the indicators that depend on geometrical and satellite data parameters. Upon this geometry, the semantic data is introduced, linking the attributes belonging to each element of the geometry (buildings and public spaces) necessary for the calculation of indicators related to semantic information. This model will gather the information necessary for both the sample building process and the full MIVES risk assessment process, both limited bay data availability and the characteristics of each case study, but aiming for replicability.

In the case of the categorization approach the information for the vulnerability assessment of the sample level will be collected. Vulnerability will be calculated for each sample building and public space as the next step, representing each category and extrapolated to the elements belonging to that category. Resulting on the vulnerability of the historic area. Then data on hazard will be added to all the elements resulting on the final risk assessment. The risk will be specific for each elements resulting on maps picturing the risk index level for each element.

Vulnerability is performed separately to the hazard indicators for the flexibility of adapting the model to different hazard scenarios. Vulnerability is related to the intrinsic characteristics of each element, and as such is a static picture of the situation in a specific moment. Hazard characteristics, on the other hand, in a climate change scenario specially, can change rapidly. Risk assessment, hence, can be performed using data belonging to a specific heat wave event, or various climate change scenarios to predict future risks.

The objective of the data models is, therefore, to provide representative information of risk within the historic areas to support the prioritization of adaptive and preventative interventions and strategies.

As a tool for the development of the models, geographic information system (GIS) was selected, in this case via the use of QGIS. GIS is a type of database containing geographic data combined with software tools for managing, analysing, and visualizing those data. GIS is a tool that provides the opportunity to work with geometric and semantic information at different levels that can be easily integrated with satellite data, as well as provide interoperability with the geographic data bases of different regions.

3.5 Conclusions

This chapter provided the methodological approach for the calculation of the vulnerability and risk indexes. The methodology is based on MIVES which structures the information in a hierarchical mode to create the decision tree composed of requirements, criteria and indicators for both buildings and public spaces. The alternatives for the indicators were defined and calculated through comparable dimensionless values by the use of value functions. Weights were then added to both criteria and requirements in order to obtain a vulnerability index.

The same approach was applied to the hazard requirement, calculated trough the same value analysis method, and the risk index was obtained. It is calculated for the whole historic area since the hazard affects all elements of the historic area equally.

The exposure in the case of heat waves is the same for the whole historic area because the data available (resolution) has the same value for the case study scale.. Therefore, its value is neglected (would be 1 for every element), and only hazard and vulnerability requirements are considered for the risk analysis.

The modelling strategy is proposed in two ways: one, through the categorization method, and two, through the full modelling including individual data for every element. The categorization aims to generate a number of sample buildings and open spaces that accurately represent the historic area. This method aims to provide a complete assessment with limited data, reducing analysis time and resources. Hence, the categories are generated using only the information or indicators that better characterise the elements under assessment. Afterwards, the selected indicators are fed with the sample elements and the results extrapolated to all the elements within the category.

The vulnerability assessment includes 11 indicators in the case of the buildings and 8 for the public spaces which are assessed by value functions to obtaine dimensionless values from 0 to 1. Weights are then assigned through the Analytic Hierarchy Process (AHP) by stablishing the relative importance, through pair-wise comparison of the different levels of the decision tree. The Risk index is obtained adding hazard indicators (4) to the vulnerability index. The analysis requirements force us to use multi-criteria methodologies and MIVES' capacity to measure information of a different nature in the same language make it suitable for our objective. In addition, it also allows using the categorization and is a friendly tool due to its tree-shaped display and the clarity with which the information and evaluation are displayed.

4 Validation of results in an case study (Bilbao)

4.1 Description of the study case

Bilbao is located in the north-west of Spain with approximately 345,000 inhabitants. The capital of Bizkaia region is located in the lower valley of the Nervión-Ibaizabal. It occupies the meander, 2 km in diameter, which describes said fluvial course at the approximate point where it becomes an estuary. The city is only 19 meters above sea level and is surrounded by two mountain ranges, which average altitude does not exceed 400 meters. Its location at the bottom of the valley and a mountainous topography have conditioned the growth of the city, which has grown towards the sea following both banks of the estuary. Even so, land limitations are again present around the artery that makes up the estuary and the port.

Figure 49. Aerial photo of Bilbao’s historic area on 2019. Source: Geoeuskadi.

The physical constraints and the strong demographic, economic and urban development experienced as a result of the industrialization process from 1876 to 1975 have ended up configuring an urban landscape with varied urban: the Bilbao de las Siete Calles (Historic area of the city), the first *Ensanche de Abando*, the second *Ensanche de Indautxu* and the peripheral neighbourhoods.

Bilbao, given its status as a protected port and crossroads, oriented its development towards commercial and mercantile activities, to which shipbuilding was also linked. The economic modernization that began in the second third of the 19th century was favoured by the existence in Bilbao of rich and abundant deposits of iron, which formed the basis of the industrial boom that lasted until the beginning of the 20th century. For these dates, the port and industrial city was consolidated as the centre of the urban agglomeration that extends to *El Abra*, with financial and service functions. During the industrial and urban expansion phase of the third quarter of the 20th century, the Bilbao metropolitan area reached a centrality that went beyond the Basque area itself and developed functions of a peninsular scale. The subsequent crisis, especially serious for the old industrialized regions, led to the economic restructuring and urban regeneration of this metropolis. In post-industrial Bilbao, the tertiary sector gains economic weight, a symbol of which is the Guggenheim Museum (1997).

The area selected as the case study is the historic district of the city of Bilbao. The historic area comprises the primitive core of Bilbao, founded in 1300 by Diego López de Haro thanks to its status as an inland port, located on the right bank of the estuary and made up of seven parallel streets connected by cross-sectional cantons, as well as its first radial expansion to the northwest. Its medieval structure had a wall built in 1334. The old church of Santiago was replaced by a Gothic temple at the end of the 14th century. Likewise, in the 15th century, outside the walls and next to the estuary, the church of *San Antón* was built. Outside the walls, convents and religious orders were established: *San Francisco, San Agustín, La Encarnación, San Andrés*. On the façade of the city towards the port, the towers and mansions of the most powerful families were concentrated, while the social fabric, in the interior streets, was made up of sailors, artisans, merchants, shopkeepers and clerks, filling up the available space.

In the mid-15th century, the need for the expansion of the city outside the walls to the northwest was raised, with streets arranged in a radial pattern. An intense phase of demographic and economic growth based on the transport and exchange of goods began at the end of the 15th century. In the middle of the 16th century, Bilbao participated in the great international commercial circuits and incorporated its own products (apart from Castilian and Navarran wool) such as iron, shipbuilding, fish and clothing, becoming the first port of Spain.

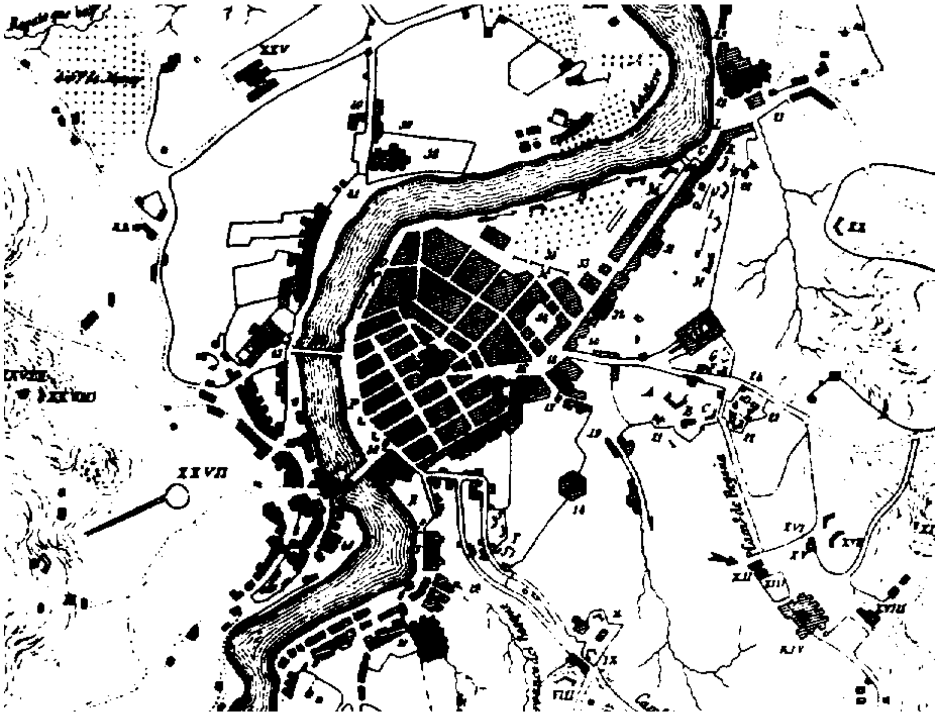


Figure 50. Historic map of Bilbao in 1835. Source (Leonardo Aurtenetxe 1989).

As a result of the great fire of 1571 and the terrible floods of 1593, the urban planning of the town was reconsidered. On the one hand, moving from the construction of wood to stone and, on the other hand, reordering the alignments, the plots of the houses and eliminating the medieval walls. In the 17th century, interventions were undertaken in spaces located outside the medieval city, such as in the surroundings of *Prado del Arenal* and *La Sendeja*, which became a new area for port activities. Likewise, in the arcades of the Ribera, quality residences were built on arches, such as the Arana Palace, which has survived to this day.

At the end of the 18th century, the population density in the town was very high and, through the Loredo Plan signed in 1786, a forceful intervention was proposed aimed at the extension of the urban fabric and the modernization of its buildings. In the last decade of this century, *El Arenal* area was consolidated, witnessing the change from the medieval city to an open and expanding city model, prior to the leap towards Abando plain on the left bank of the estuary.

Figure 51. Bilbao’s plan from 1889, showing the development of the “Ensanche” area. Source: archive of municipality of Bilbao.

At the end of the 19th century, the situation of urban congestion coupled with continuous flooding made Bilbao one of the most unhealthy European cities with the highest death rate, the estuary being a source of infection. In this situation, the new Ensanche was planned in 1873, which meant the definitive expansion of the city towards the fertile plain of Abando. Despite this, the old part of the city retained its centrality for some time, reforming itself internally.

Figure 52. Bilbao’s *Plaza vieja* in 1854, before the Ribera market was built.

At the beginning of the 20th century, after the creation of the outer port and the Abando docks, the port activity progressively disappeared in the old quarters and new supply activities appeared (grocers, bartenders). Likewise, the central food market (Ribera market) is consolidated culminating in the current building built in 1930, occupying the historic main square.

The floods that took place in 1983 marked the beginning of a profound rehabilitation task, both of homes and public buildings, in the hands of the municipality. Today we can say that at the level of external configuration, there are no examples of facades prior to the 17th century in the historic area, although at the internal level (distribution, communication nuclei) we can find elements of historical survival. There is currently a fairly homogenized urban landscape with buildings of four heights and in certain areas with an element that was incorporated in the mid-nineteenth century, the viewpoint or sunroom, which became a recognizable architectural resource in the bourgeois residences built between 1890 and 1930.

4.1.1 Area of study

As detailed in the introduction of this chapter, the area selected as the case study is the historic district or *Casco Viejo* of the city of Bilbao (Figure 53). For the present study most of the historical and protection information has been gathered from the *Plan Especial De Rehabilitación Del Casco Viejo De Bilbao* (Special Rehabilitation Plan for the Historic City Core of Bilbao) approved in 1998 with the goal of addressing the preservation and re- structuring of the old town. This plan details the configuration and morphology of the different areas that compose the old quarters.

The special rehabilitation plan is divided into 6 sectors, 5 of which fall into the study area. These sectors are differentiated according to the historical morphology and growth of the city. Sector 1 is the *Siete Calles* district, with a layout inherited from the 10th century in its configuration; from the 16th century in the palatial specialization of the head plots of the Ribera, and from the second half of the 19th century on its house typology. Perpendicular to the estuary, the streets are the organising element, marking a buildable intermediate of 32 meters with 5.50m streets; such organization is justified by a tradition inherited from the Roman grid and by the water and waste evacuation system in medieval times. Although of secondary importance, 2.60 m wide cantons cut the building groups in *manzanas* (blocks) of irregular dimension. It is an area characterised by a row organization of the plots which measurement does not respond to a fixed module, ranging from 3.50 meters to 4 meters even 6, subordinated to the capacity of the owner and to the technological constants of wood (main structural material historically) and superimposing in height the two uses of housing and commerce or artisan workshop. Originally, the heart of the Old Quarter was surrounded by walls and consisted of three parallel streets. Later, it became necessary to take down the walls and build four streets perpendicular to the river, along with the first three. Since 1979, this area has been a pedestrian precinct, with hundreds of commercial establishments, bars and restaurants.

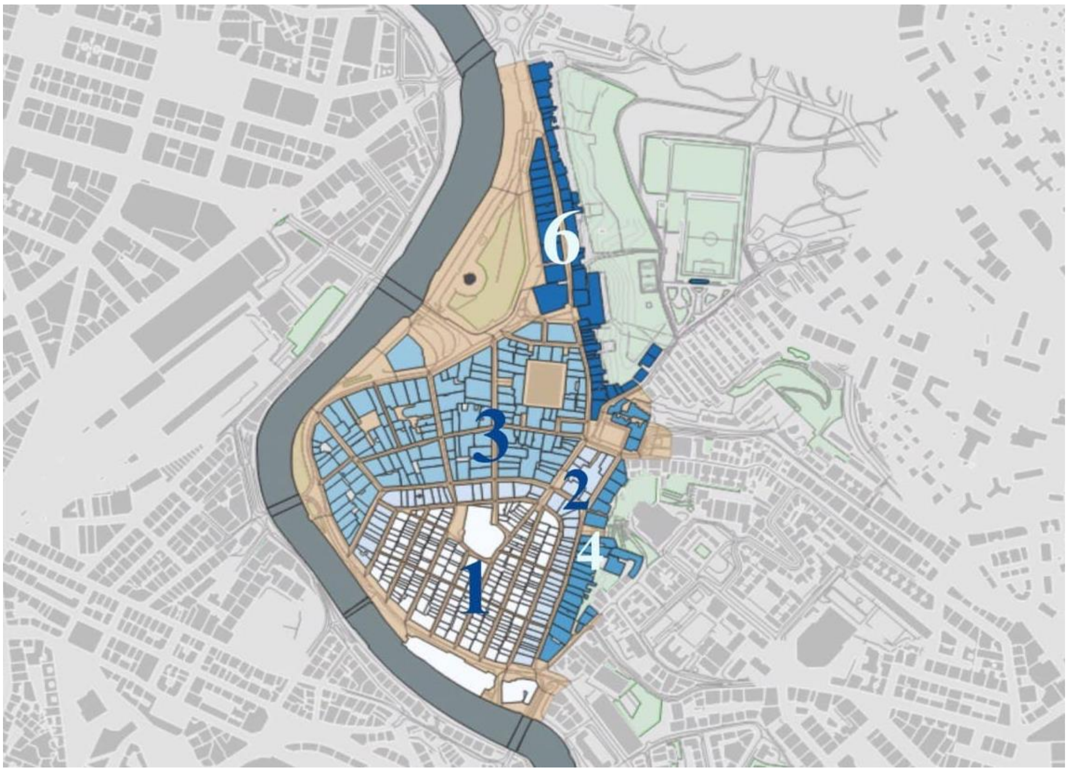


Figure 53. The area selected as case study. Historic district of the city of Bilbao and sectors of study.

Sector 2 or *Rondas* is of typical appearance on the walled cities, within a dynamics of natural growth. The occupational type responds to the same logic, in a long and narrow plot, perpendicular to the wall, forming short-bottomed blocks with direct exit on both sides and entrance from the inner city side. Currently, the original typologies have been replaced by new buildings of the late nineteenth and early twentieth centuries, allowing a greater use in height. Those replaced in the last century have six heights for the most part, while those of the 20th century reach the seven heights.

Sector 3 includes *Ensanche Ribera* y *Plaza Nueva*. Originally urbanized during the 17th century, this was a land semi invaded by the tide, receiving the name of *Arenales*. The Ordinances unified constructive criteria in materials and even cornices; façade reforms and additions unified the image of the city. Baroque - neoclassic plot characterized by buildings of oak wood structure as structural support facing the shortage of good stone quarries.

Sector 4 or *Arrabales* constitute axes of natural growth extramural, starting the settlements from the singular elements generators of the new plot. The type of plot is very varied, so a common norm cannot be drawn for this area.

Sector 6 or *Sendeja-Epalza* area developed in the 19th century which parcel type is homogeneous in the block *Sendeja-Epalza* and more irregular in the front of *Askao*. As the edge of this sector is the entire *Mallona* reserve, in his day concentrating certain "services" of the Villa (cemetery, walks, as well as garden spaces linked to convents), today an important green area for the city.

4.2 The model and data base

The implementation of the methodology was carried out through a GIS model. For the generation of this model, two main steps were taken. First, the generation of the geometry composed of the buildings and the open spaces as polygons. Secondly, inclusion of the semantic information of the polygons regarding the indicators data for each of the elements.

For the geometry of the model, several sources were used. The building 2D geometry was collected from the Basque Government geographical information database (Geoeuskadi), and easily added to the model as a polygon layer. Information on the topography of the terrain and 3D geometry of the buildings (heights and number of floors) was gathered using a combination of the data gathered from Geoeuskadi and the cadastre, Lidar and the Digital Terrain Model (DTM). LiDAR - Light Detection and Ranging – data is a system that generates a point cloud of the ground by means of an airborne laser scanner and represents the Digital Surface Model (DSM) of the area of interest (Figure 54). Cadastral and Geoeuskadi information was used in shape format, containing the geometry of the footprints of buildings in the area of interest. DTM data is a false 3D representation of topography from a terrestrial zone that is stored as a matrix of points with heights (Figure 54). By using the LIDAR and DTM data, the actual height of the buildings and their altitudes was obtained. In the case of the public spaces, only the street axis were available, so the polygons for the streets and squares were done manually, using the axis layer and the limits set by the buildings.

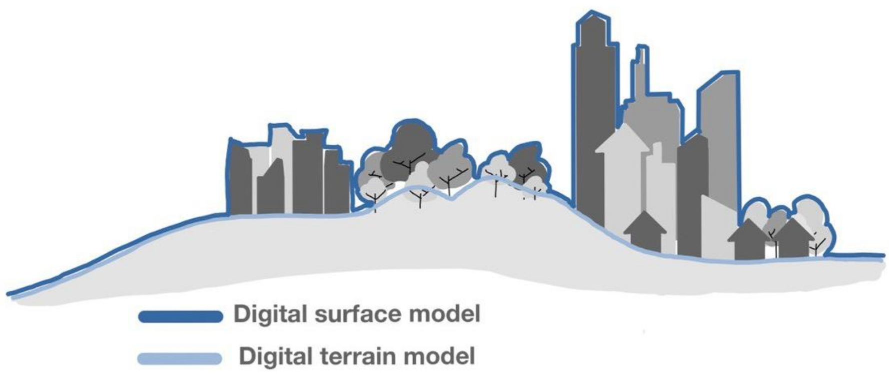


Figure 54. Digital surface model vs digital terrain model (DSM and DTM).

The GIS model has been completed for the case study of Bilbao with semantic information available from public data sources. The data has been collected from different sources and worked in two different ways. The majority of the data has been collected from the Basque Government geographical information database (Geoeuskadi), the cadastre and the census, and processed to automatically include in the data model. The data related to physical and environmental properties such as SVF, NDVI, solar radiation etc. has been obtained from either satellite data (Copernicus and Landsat) or through the use of the satellite data through the Urban Multi-scale Environmental Predictor (UMEP) for QGIS (Lindberg et al. 2018). In addition to this, the data from the Special

Rehabilitation Plan for the Historic City Core of Bilbao, namely the protection status of the buildings, was introduced manually. The state of conservation of the buildings was gathered via field work done by the author, as it was not available. As not all the data mentioned in the previous steps was available some indicators could not be used, in particular: vulnerable population, the link to historical events and the presence of the elevator in the case of buildings, and albedo, air pollution and the link to historical events in the case to public spaces.

4.2.1 Statistical overview of the historic area

For the proper categorization of the area that will follow in section 4.3, a statistical overview of the area is a necessary step (Figure 55). Every historic area is different; hence, to obtain a balance between the categories and the representativeness for the elements under analysis, a statistical overview will help obtain ranges for the different indicators. The figures show the distribution of the parameters chosen for the characterization in the Bilbao historic area, first for buildings (Figure 56), and then for urban spaces (Figure 57).

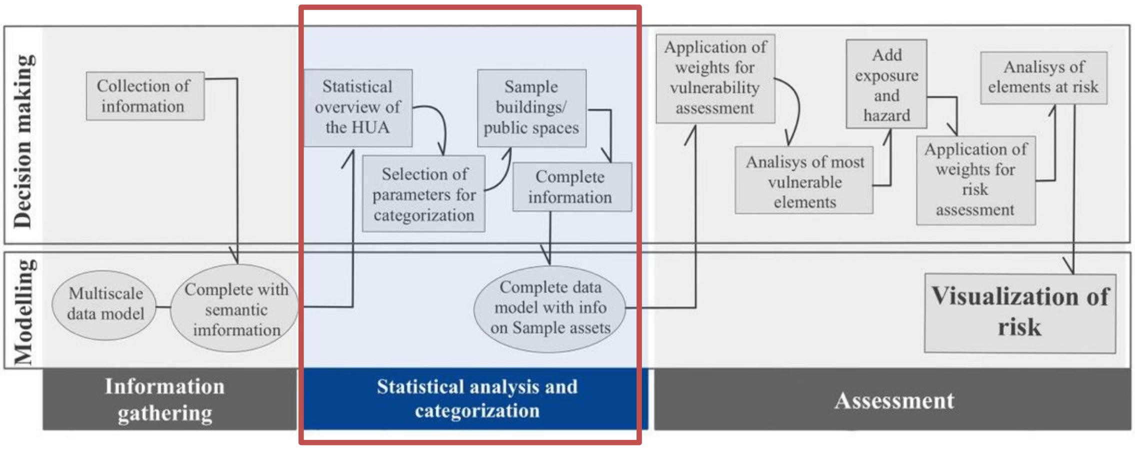
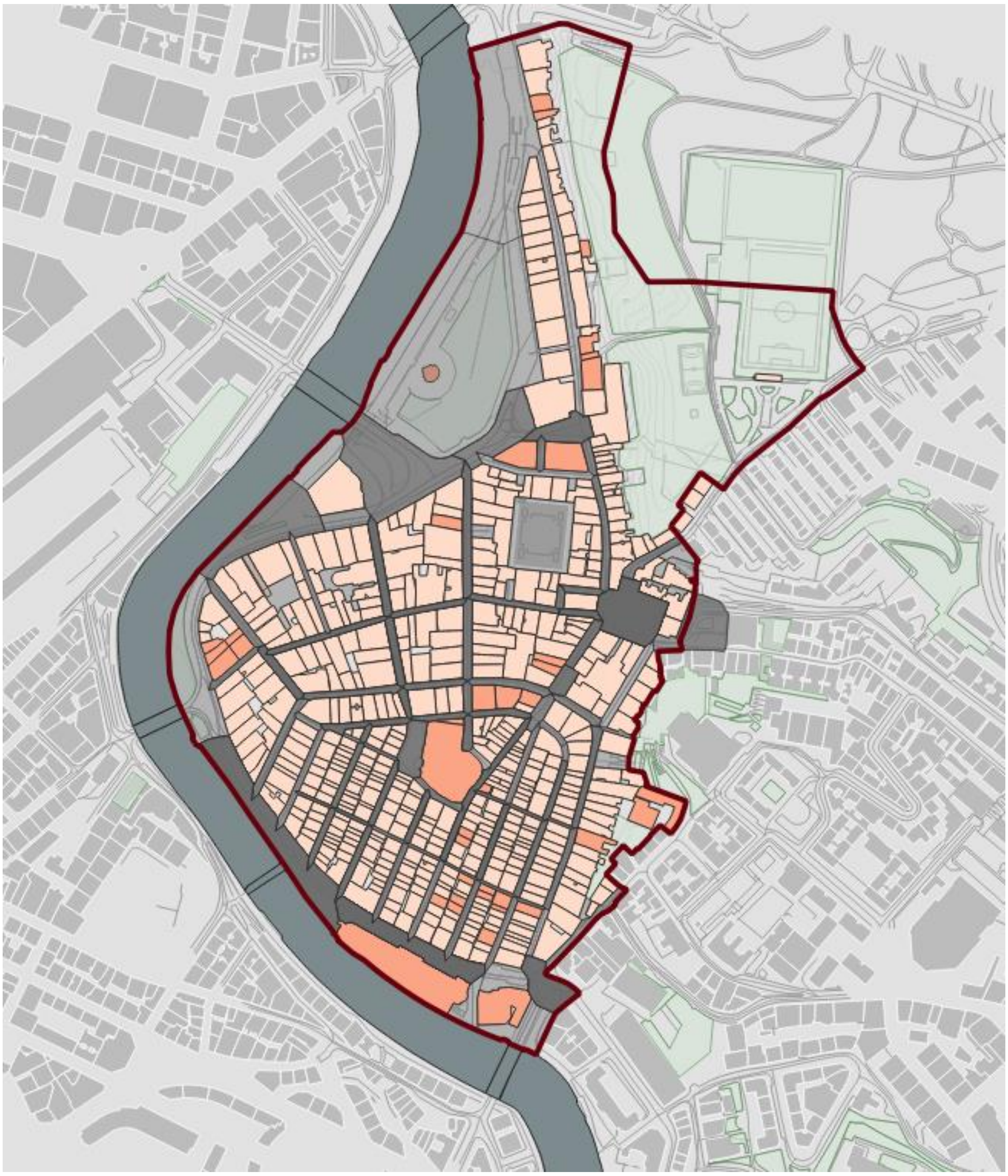


Figure 55. Workflow process from the collection of information to the visualization of, statistical analysis, categorization and risk.

The indicators chosen for building categorization, as shown in chapter 3, were solar radiation, year of construction, use, protection level and population density.

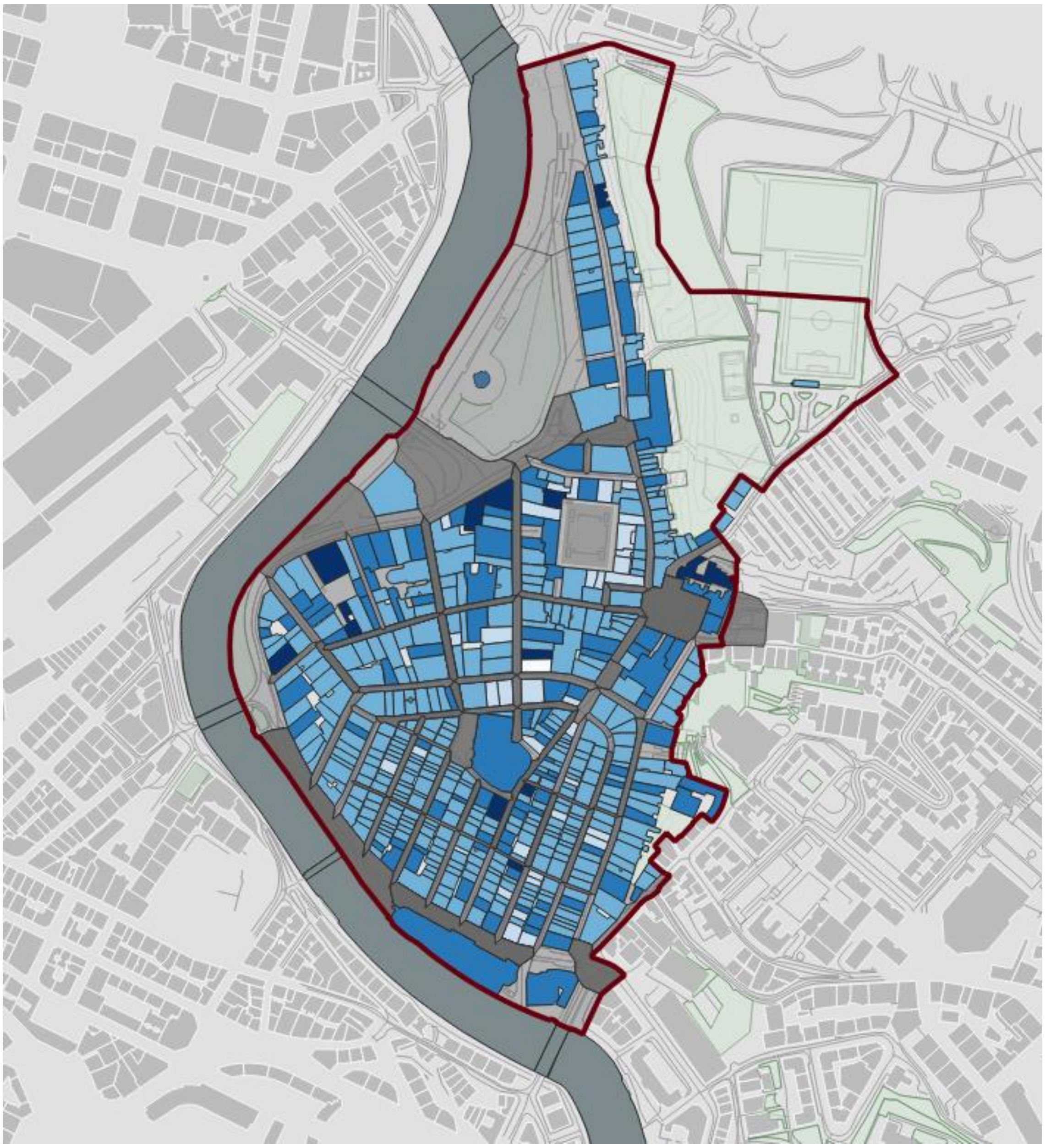
Statistical overview of buildings

Solar radiation



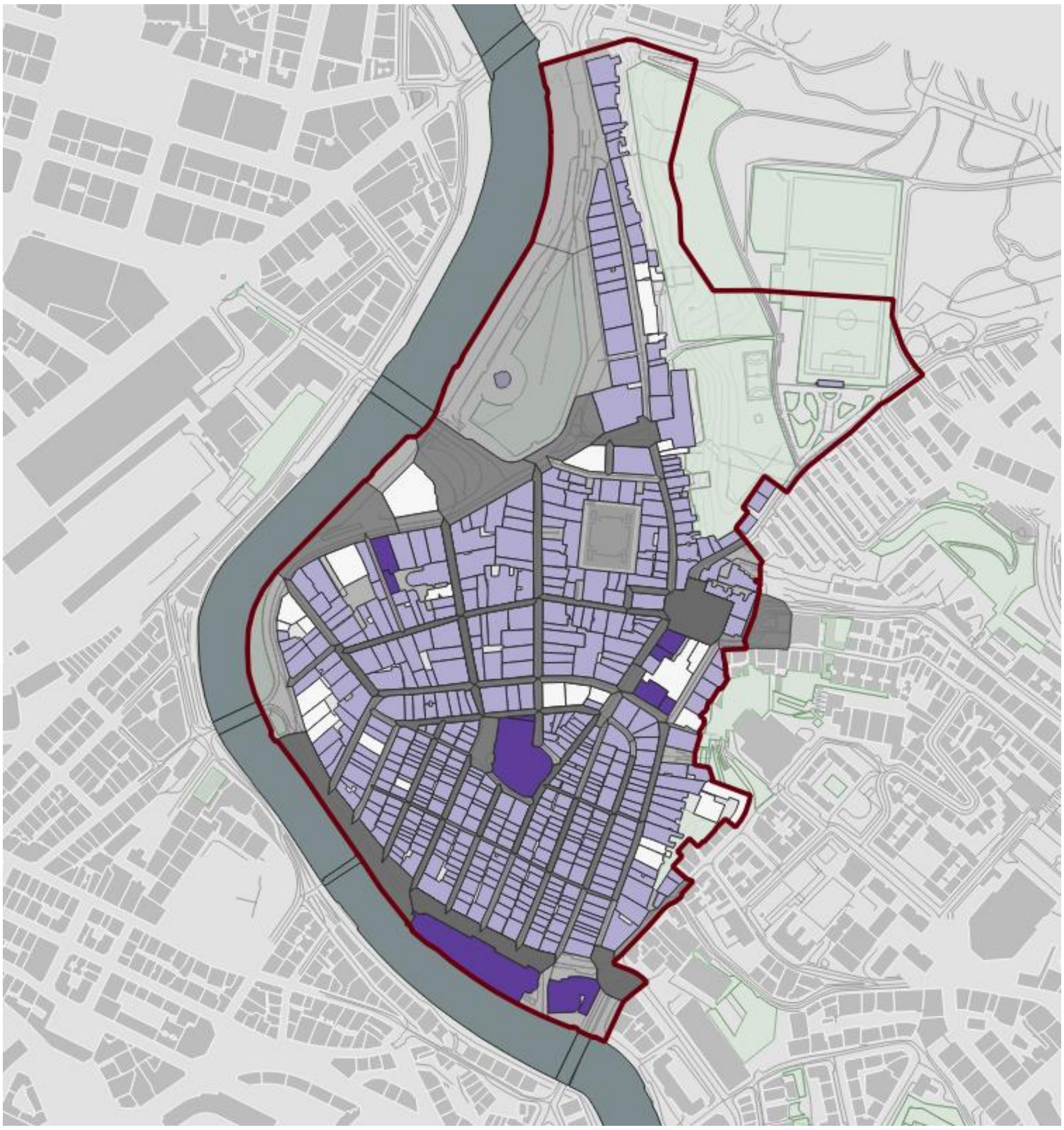
		Number of buildings	Colour
Very low	≤ 0.2	0	
Low	0.2 to 0.4	0	
Medium	0.4 to 0.7	40	
High	≥ 0.7	483	

Year of construction (vulnerability of materials)



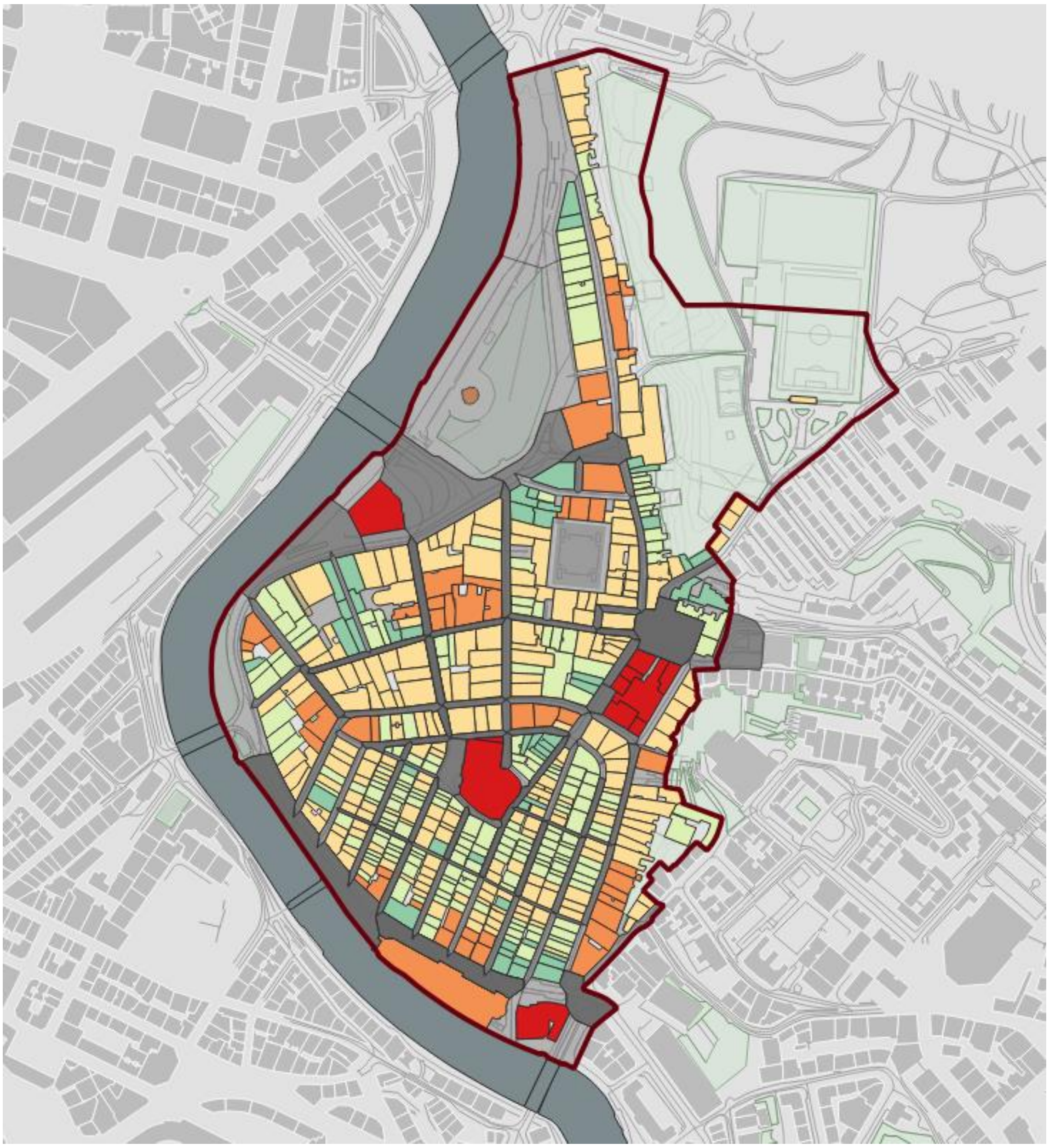
	Number of buildings	Colour
≥ 2006	14	
1920 to 2006	103	
1850 to 1920	369	
1700 to 1850	36	
≤ 1700	1	

Primary use



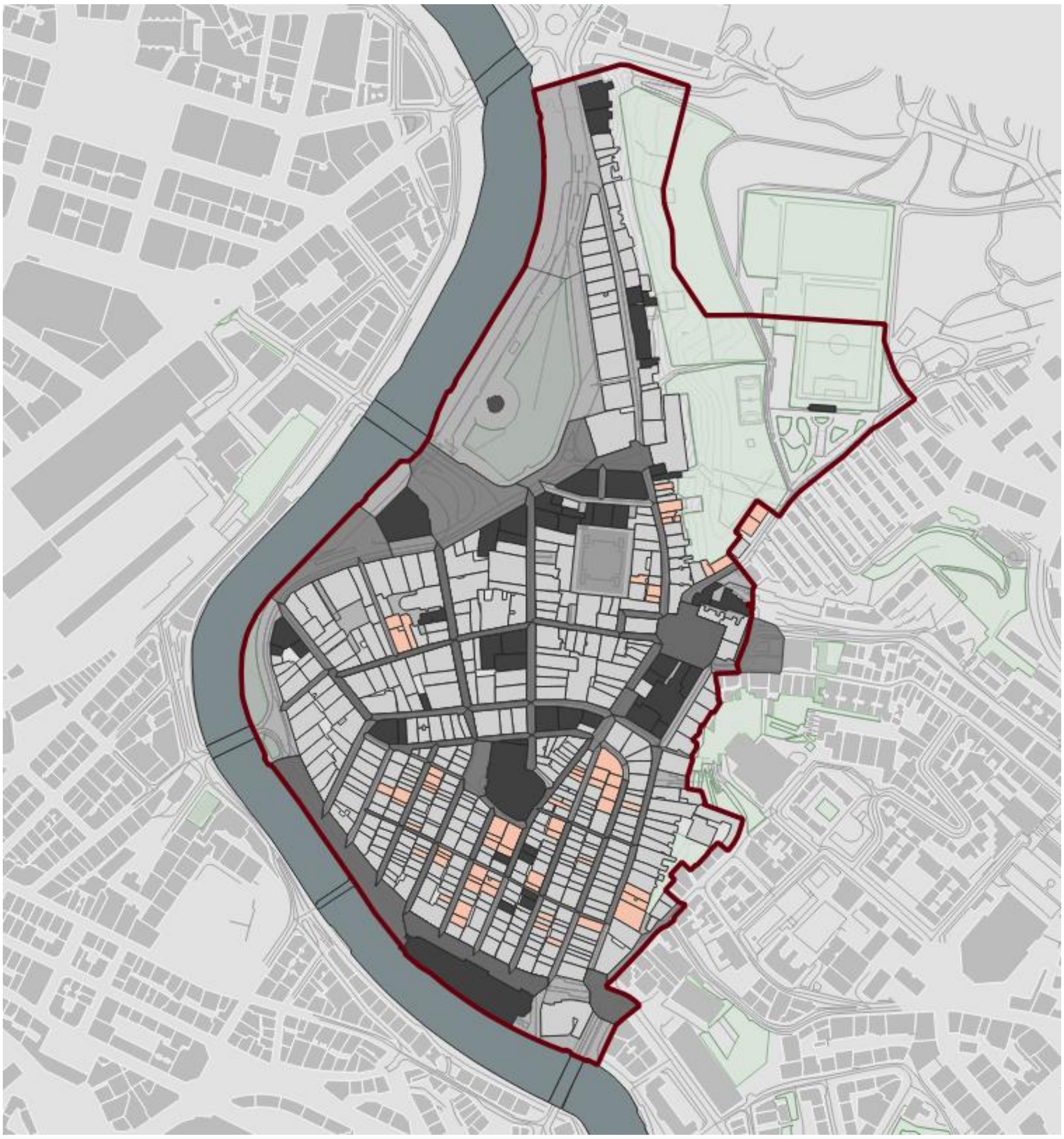
	Number of buildings	Colour
Residential	484	
Industrial	0	
Public Use	29	
Touristic	10	

Protection level



	Number of buildings	Colour
Monument	10	
Integral	42	
Typological	215	
Basic / ambiental	194	
None	62	

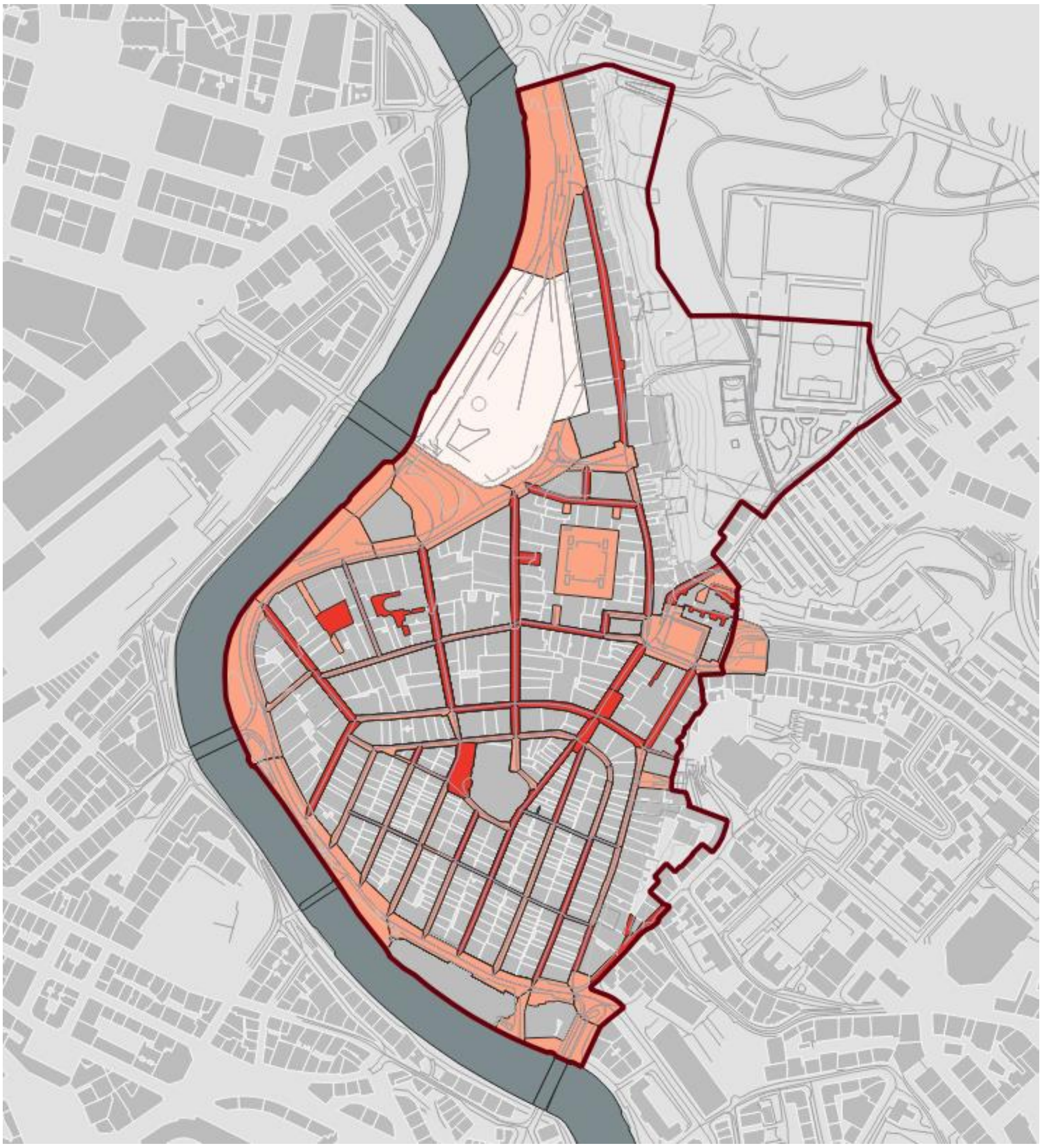
Population density



		Number of buildings	Colour
Empty	0	60	
Low	$x < 0.02$ habs/m^2	390	
medium	$0.02 < x < 0.05$ habs/m^2	73	
high	$0.05 > x$ habs/m^2	0	

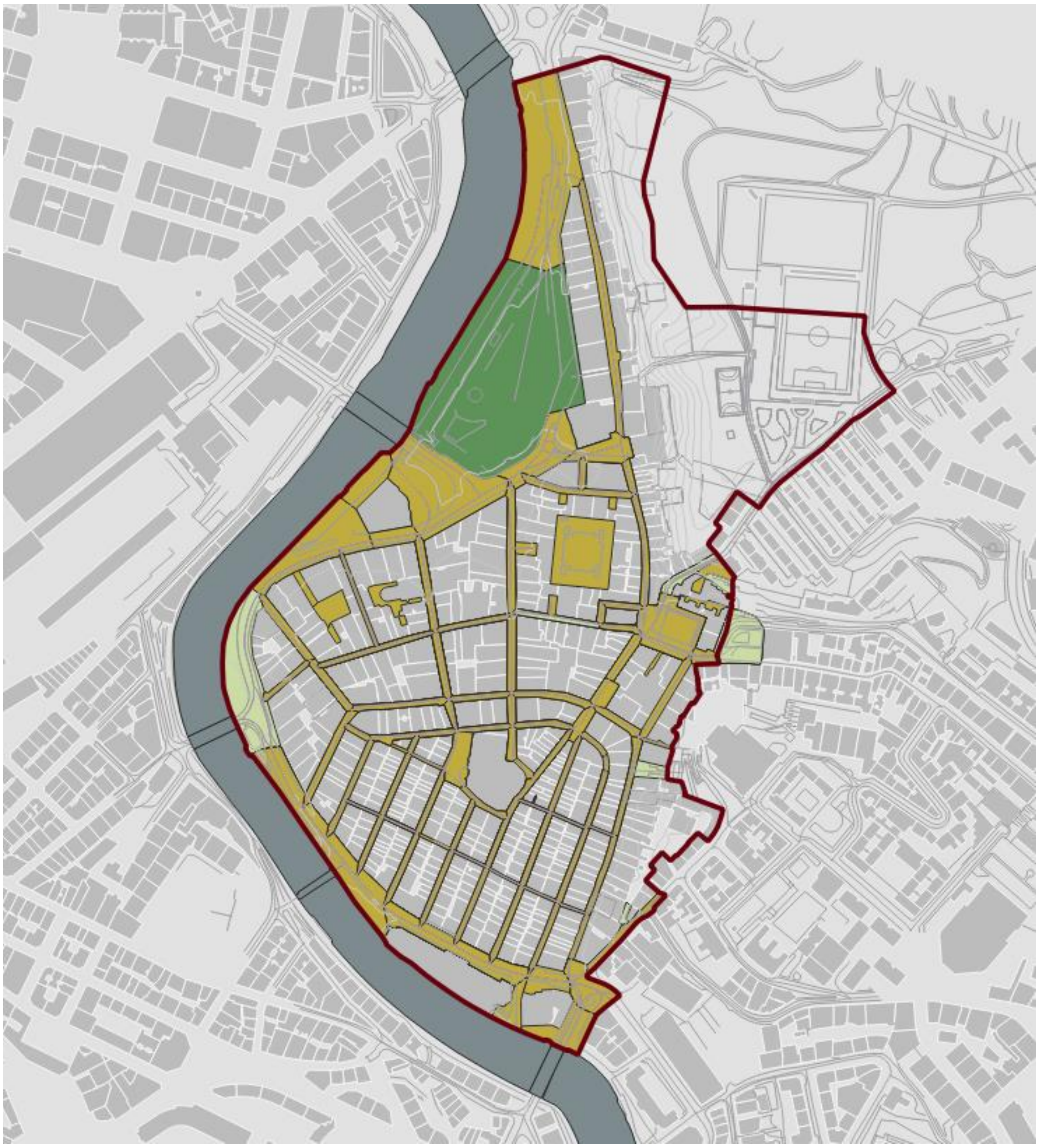
Statistical overview of public space

Solar radiation



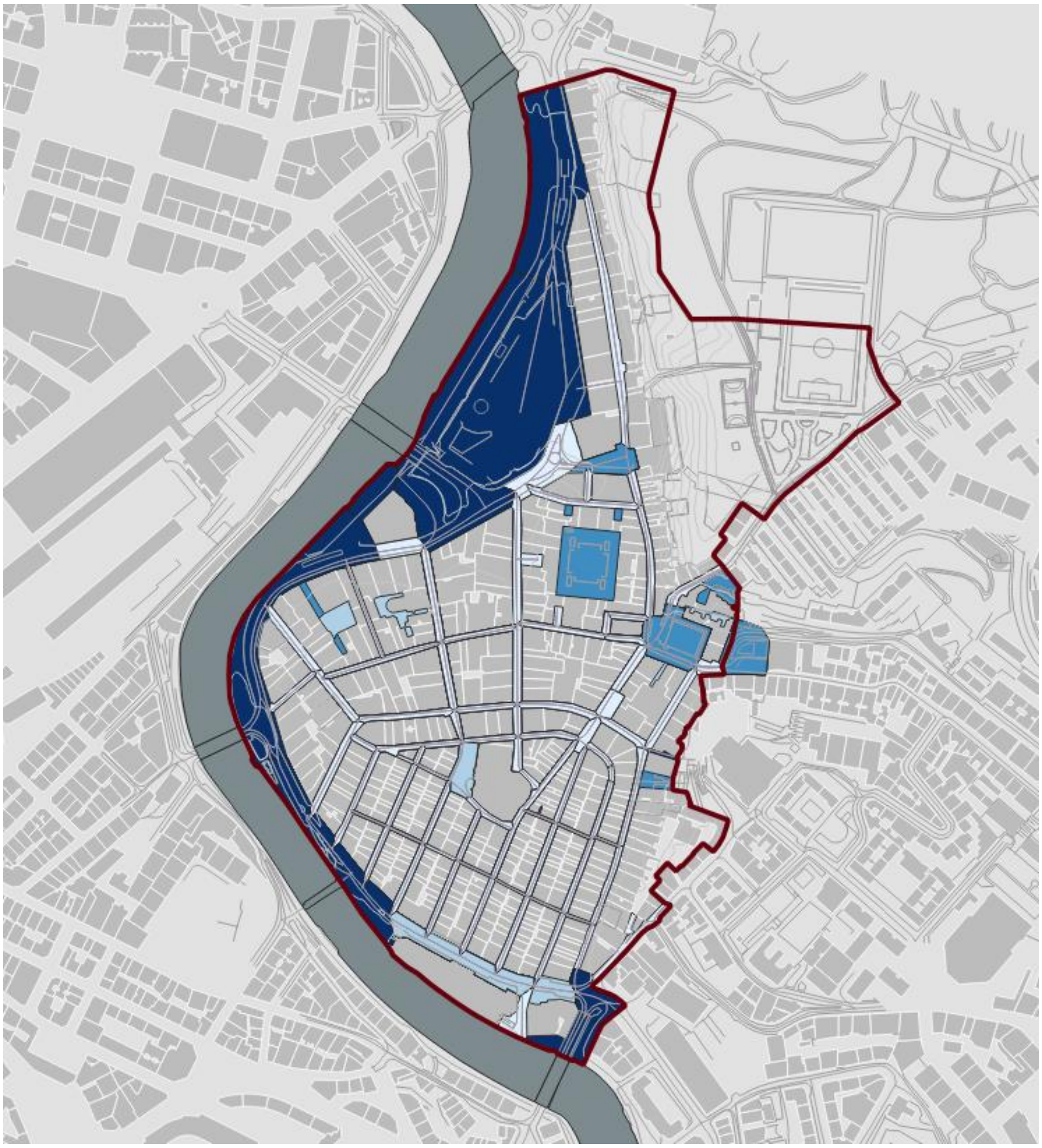
		Number of spaces	Colour
Very low	**≤ 0.2**	0	
Low	**0.2 to 0.4**	39	
Medium	**0.4 to 0.7**	61	
High	**≥ 0.7**	7	

NDVI



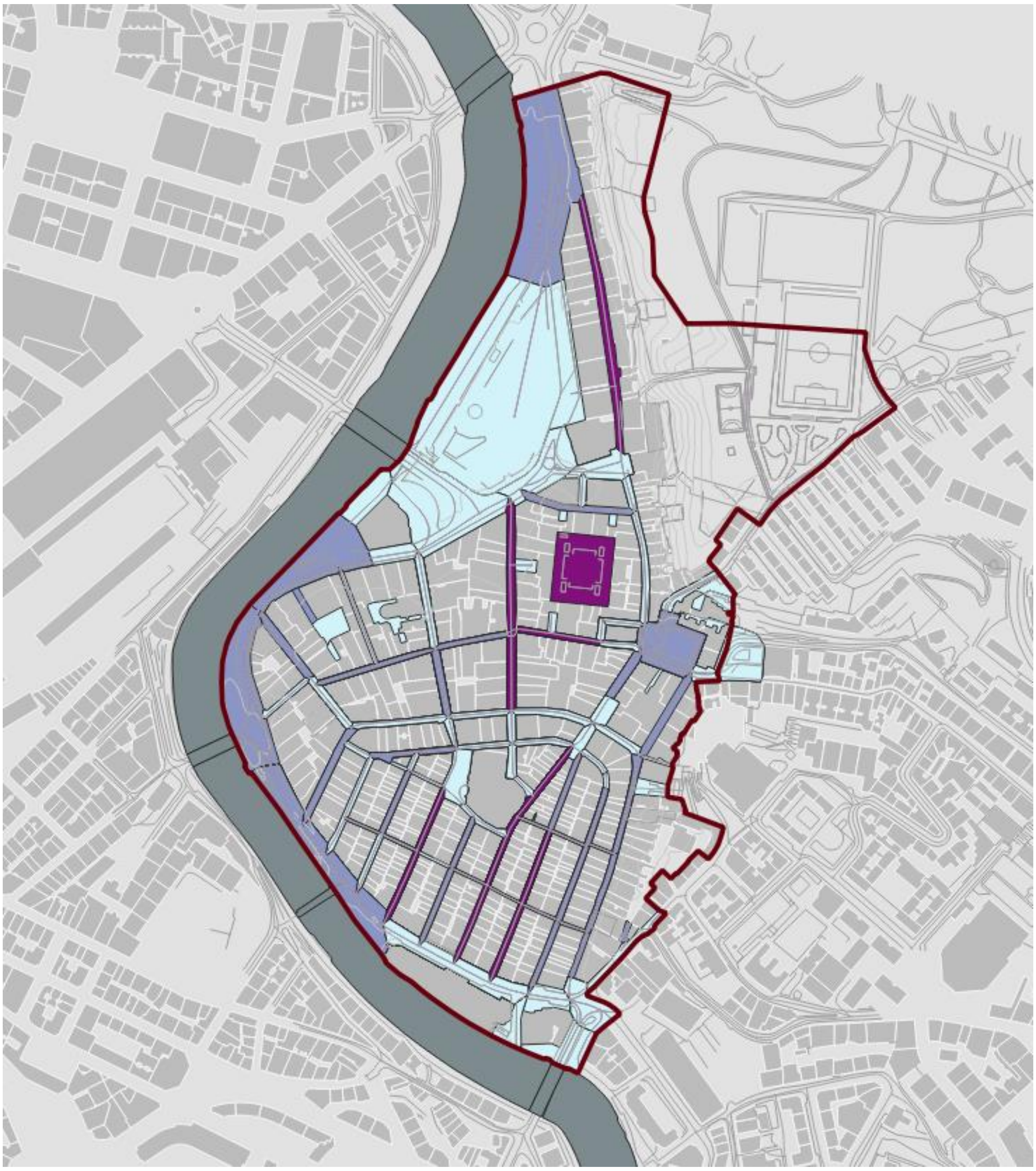
		Number of spaces	Colour
Low	≤ 0.2	98	
Medium	0.2 to 0.5	8	
High	≥ 0.5	1	

SVF



		Number of spaces	Colour
Very low	≤ 0.35	78	
Low	0.35 to 0.5	7	
Medium	0.5 to 0.65	12	
High	≥ 0.65	10	

Relevance



		Number of spaces	Colour
Low	**≤ 5**	71	
Medium	**5 to 15**	26	
High	**≥ 15**	10	

4.3 Categorization. Sample buildings and public spaces

As explained in section 2 of this paper, the first step of the workflow (Figure 37) is the collection of information and the building of a multiscale data model, which in turn provides a statistical overview of the historical area and feeds the sample building categorization process.

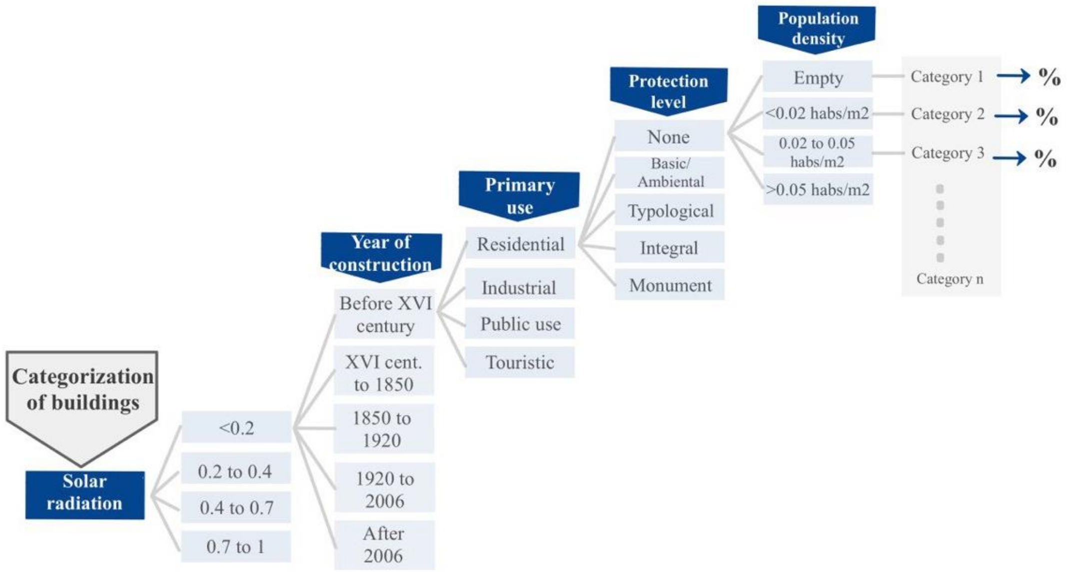


Figure 56. Parameters for the characterization of buildings.

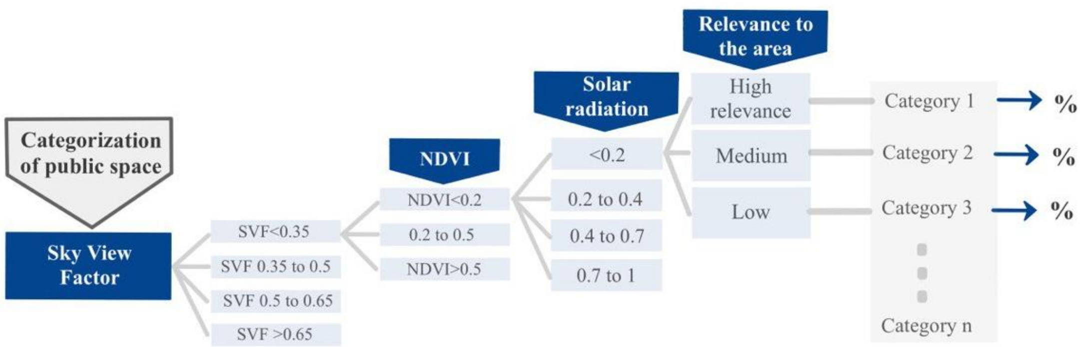


Figure 57. Parameters for the characterization of public spaces.

Therefore, following the results of the statistical overview of the area, the categories were generated following the selected parameters, and with a threshold of 2% for representation. The following Table 64 and Table 66. Generation of categories for public spaces.show the generation of categories for buildings and public space.

Solar radiation: Alt	% of total	Year of construction: Alt	% of total	no of buildings	Use: Alt	% of total	no of buildings	Protection level: Alt	% of total	no of buildings	Population density: Alt	% of total	no of buildings
Very low	0												
Low	0												
Medium	7.65%	before 1700	0.00%	0									
		1800/1850	0.76%	4									
		1850/1920	3.63%	19	Residential	3.63%	19	none	0.00%	0			
								Basic	2.10%	11	0	0.00%	0
											less than 0.02	1.53%	8
											0.02-0.05	0.57%	3
											0.05	0.00%	0
								Typo	1.34%	7			
								Integral	0.19%	1			
								Monument	0.00%	0			
					Industrial	0.00%	0						
					Public	0.00%	0						
					Touristic	0.00%	0						
		1920/2006	2.87%	15	Residential	1.15%	6						
					Industrial	0.00%	0						
					Public	0.96%	5						
					Touristic	0.76%	4						
		more than 2006	0.38%	2									
High	92.35%	before 1700	0.38%	2									
		1800/1850	5.16%	27	Residential	5.16%	27	none	0.19%	1			
								Basic	1.53%	8			
								Typo	3.06%	16	0	0.00%	0
											less than 0.02	2.87%	15
											0.02-0.05	0.19%	1
											0.05	0.00%	0
								Integral	0.38%	2			
								Monument	0.00%	0			
					Industrial	0.00%	0						
					Public	0.00%	0						
					Touristic	0.00%	0						
		1850/1920	65.01%	340	Residential	62.52%	327	none	2.10%	11	0	0.19%	1
											less than 0.02	1.53%	8
											0.02-0.05	0.38%	2
											0.05	0.00%	0
								Basic	28.30%	148	0	0.96%	5
											less than 0.02	19.12%	100
											0.02-0.05	8.22%	43
											0.05	0.00%	0
								Typo	28.11%	147	0	1.53%	8
											less than 0.02	22.75%	119
											0.02-0.05	3.82%	20
											0.05	0.00%	0
								Integral	3.82%	20	0	0.76%	4
											less than 0.02	2.87%	15
											0.02-0.05	0.19%	1
											0.05	0.00%	0
								Monument	0.19%	1			

Solar radiation: Alt	% of total	Year of construction: Alt	% of total	no of buildings	Use: Alt	% of total	no of buildings	Protection level: Alt	% of total	no of buildings	Population density: Alt	% of total	no of buildings
High	92.35%	1850/1920	65.01%	340	Industrial	0.00%	0						
					Public	2.29%	12	none	0.00%	0			
								Basic	0.96%	5			
								Typo	0.76%	4			
								Integral	0.38%	2			
								Monument	0.19%	1			
					Touristic	0.19%	1						
		1920/2006	19.31%	101	Residential	16.63%	87	none	6.12%	32	0	1.72%	9
											less than 0.02	3.63%	19
											0.02-0.05	0.76%	4
											0.05	0.00%	0
								Basic	4.02%	21	0	0.38%	2
											less than 0.02	3.25%	17
											0.02-0.05	0.38%	2
											0.05	0.00%	0
								Typo	4.78%	25	0	0.38%	2
											less than 0.02	3.63%	19
											0.02-0.05	0.76%	4
											0.05	0.00%	0
								Integral	1.72%	9			
								Monument	0.00%	0			
					Industrial	0.00%	0						
					Public	1.72%	9						
					Touristic	0.96%	5						
		more than 2006	2.29%	12	Residential	1.91%	10						
					Industrial	0.00%	0						
					Public	0.19%	1						
					Touristic	0.00%	0						

Table 64. Generation of categories for buildings.

The buildings categories include 367 buildings of the total of 523, hence, the representation is 70.17%.

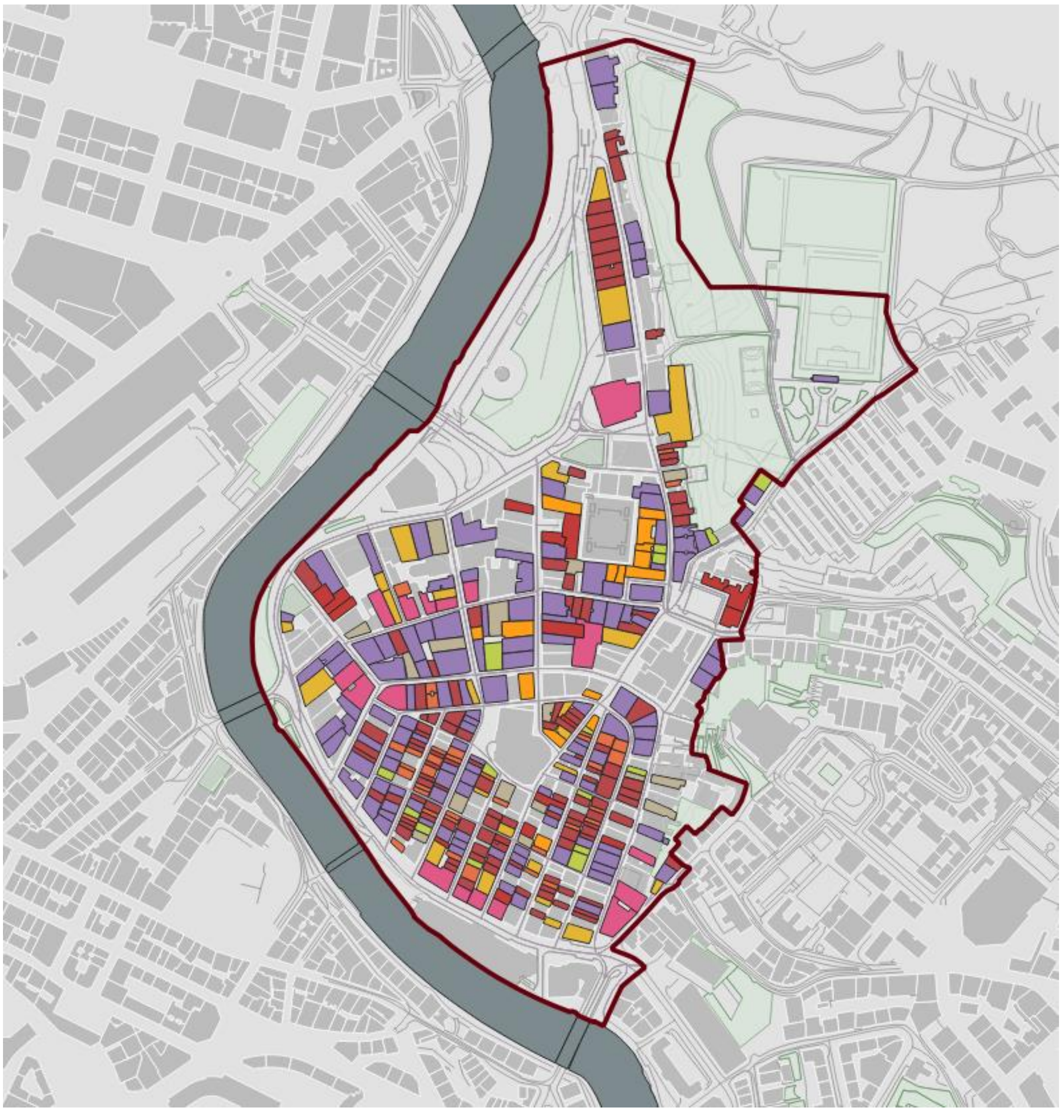


Figure 58. Buildings categories for the case study of Bilbao.

Solar radiation	Year of construction	Use	Protection level	Population density	% of total		
High	1800/1850	Residential	Typo	less than 0.02	2.87%	Category 1	
	1850/1920		Basic	less than 0.02	19.12%	Category 2	
				0.02-0.05	8.22%	Category 3	
			Typo	less than 0.02	22.75%	Category 4	
				0.02-0.05	3.82%	Category 5	
			Integral	less than 0.02	2.87%	Category 6	
	1920/2006		none	less than 0.02	3.63%	Category 7	
			Basic	less than 0.02	3.25%	Category 8	
			Typo	less than 0.02	3.63%	Category 9	

Table 65. Buildings categories for the case study of Bilbao.

SVF		NDVI			Solar radiation			Relevance		
Alt	**% of total**	**Alt**	**% of total**	**no. of buildings**	**Alt**	**% of total**	**no of buildings**	**Alt**	**% of total**	**no of buildings**
> 0,65	9.35%	< 0.2	7.48%	8	Very low	0.00%	0			
					Low	0.00%	0			
					Medium	7.48%	8	Low	3.74%	4
								Medium	3.74%	4
								High	0.00%	0
					High	0.00%	0			
		0.2 to 0.5	0.93%	1						
		> 0.5	0.93%	1						
0.5 to 0.65	11.21%	< 0.2	8.41%	9	Very low	0.00%	0			
					Low	0.00%	0			
					Medium	8.41%	9	Low	5.61%	6
								Medium	1.87%	2
								High	0.93%	1
					High	0.00%	0			
		0.2 to 0.5	2.80%	3	Very low	0.00%	0			
					Low	0.93%	1			
					Medium	1.87%	2			
					High	0.00%	0			
		> 0.5	0.00%	0						
0.35 to 0.5	6.54%	< 0.2	6.54%	7	Very low	0.00%	0			
					Low	4.67%	5			
					Medium	1.87%	2			
					High	0.00%	0			
		0.2 to 0.5	0.93%	1						
		> 0.5	0.00%	0						
< 0.35	72.90%	< 0.2	69.16%	74	Very low	0.00%	0			
					Low	26.17%	28	Low	11.21%	12
								Medium	11.21%	12
								High	3.74%	4
					Medium	38.32%	41	Low	26.17%	28
								Medium	7.48%	8
								High	3.74%	4
					High	4.67%	5	Low	4.67%	5
								Medium	0.00%	0
								High	0.00%	0
		0.2 to 0.5	2.80%	3	Very low	0.00%	0			
					Low	1.87%	2			
					Medium	0.00%	0			
					High	0.93%	1			
		> 0.5	0.00%	0						

Table 66. Generation of categories for public spaces.

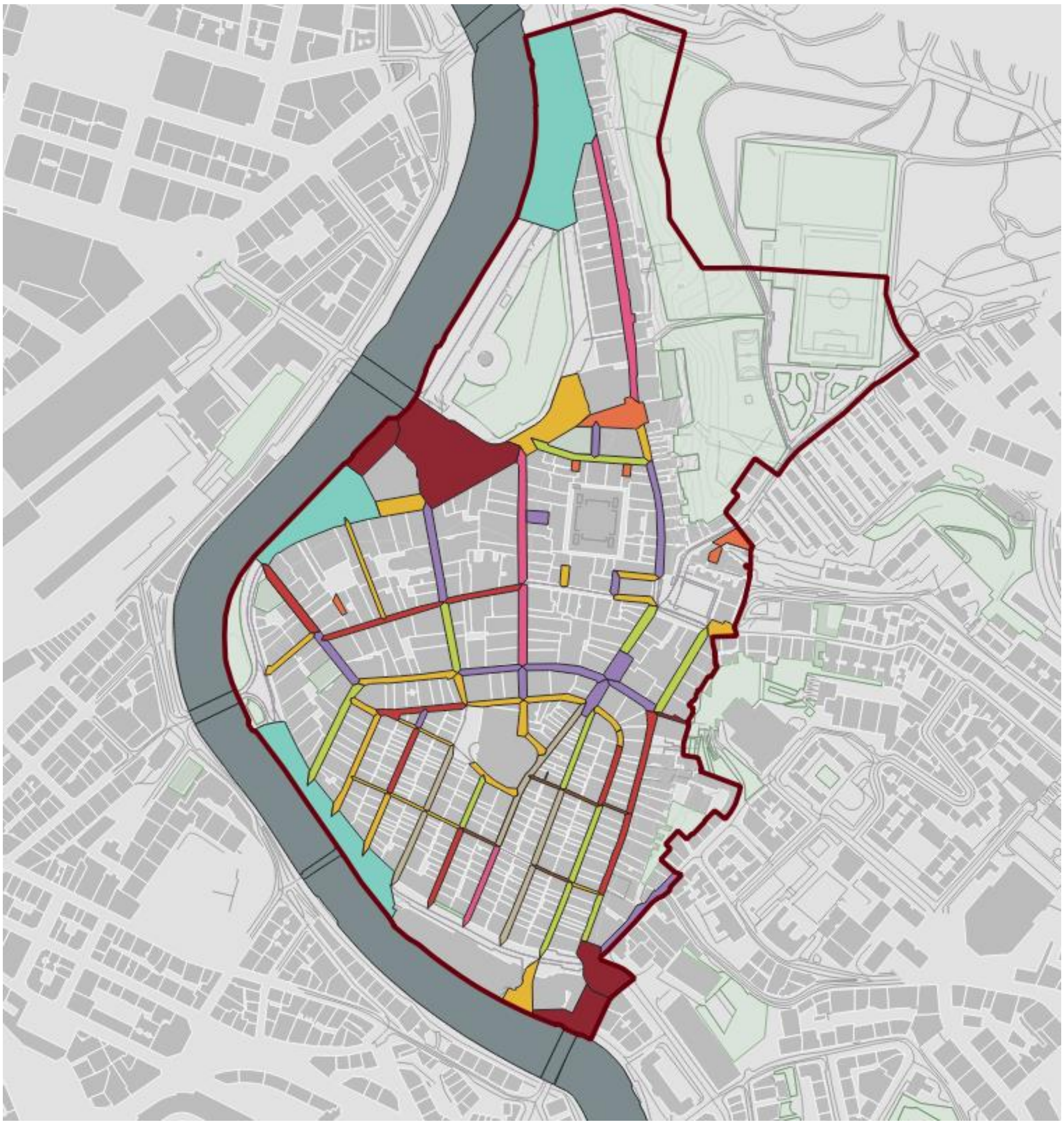


Figure 59. Public space categories for the case study of Bilbao.

SVF	NDVI	Solar radiation	Relevance	% of total		
> 0.65	< 0.2	Medium	Low	3.74%	Category 1	
			Medium	3.74%	Category 2	
0.5 to 0.65		Medium	Low	5.61%	Category 3	
< 0.35		Low	Low	11.21%	Category 4	
			Medium	11.21%	Category 5	
			High	3.74%	Category 6	
		Medium	Low	26.17%	Category 7	
			Medium	7.48%	Category 8	
			High	3.74%	Category 9	
		High	Low	4.67%	Category 10	

Table 67. Buildings categories for the case study of Bilbao.

4.3.1 Sample buildings and public spaces

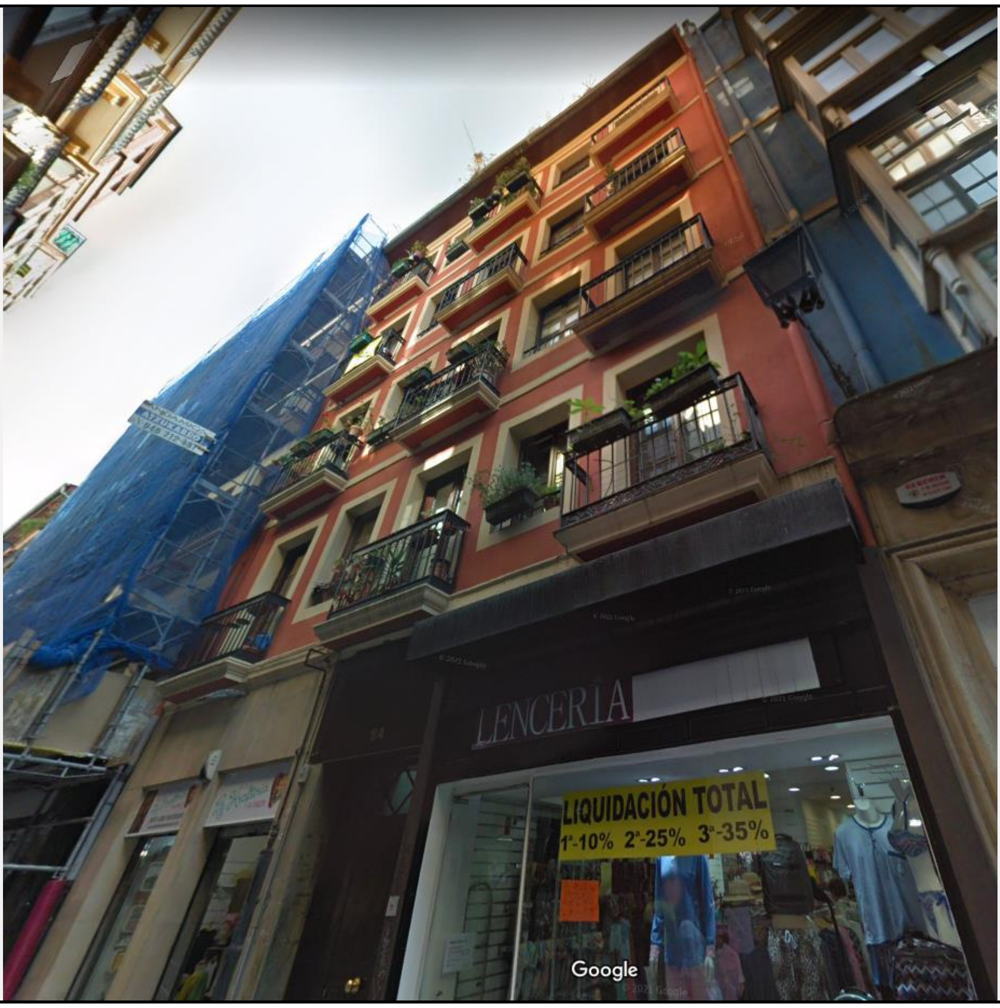
For the vulnerability assessment through the sample elements, semantic information on the sample building and public spaces was completed and then extrapolated to the elements of the same category.

Sample buildings

Category 1	ID. 224	Loteria street, nº2

Indicator		Value	Weight
Solar radiation		0.86	**0.68**
Acoustic pollution		63.13 dBA	**0.97**
Population density		0.012	**0.12**
Date of construction	Thermal comfort	1824	**0.40**
	Vulnerability of materials		**0.40**
State of conservation		Good	**0.00**
Primary use		Residential	**0.82**
Level of protection		Medium / Typological	**0.59**

Category 2	ID. 430	Artekale street, nº24



Indicator		Value	Weight
Solar radiation		0.82	**0.66**
Acoustic pollution		48.4 dBA	**0.00**
Population density		0.008	**0.13**
Date of construction	Thermal comfort	1898	**0.40**
	Vulnerability of materials		**0.40**
State of conservation		Good	**0.00**
Primary use		Residential	**0.82**
Level of protection		Basic / ambiental	**0.59**

Category 3	ID. 318	Barrenkale street, nº13

Indicator		**Value**	**Weight**
Solar radiation		0.8	**0.64**
Acoustic pollution		61.72 dBA	**0.95**
Population density		0.008	**0.31**
Date of construction	Thermal comfort	1890	**0.40**
	Vulnerability of materials		**0.40**
State of conservation		Good	**0.00**
Primary use		Residential	**0.82**
Level of protection		Basic / ambiental	**0.28**

Category 4	ID. 186	Loteria street, nº3

<table>
<tr><th colspan="2">Indicator</th><th>Value</th><th>Weight</th></tr>
<tr><td colspan="2">Solar radiation</td><td>0.78</td><td>0.61</td></tr>
<tr><td colspan="2">Acoustic pollution</td><td>63.72 dBA</td><td>0.97</td></tr>
<tr><td colspan="2">Population density</td><td>0</td><td>0.00</td></tr>
<tr><td rowspan="2">Date of construction</td><td>Thermal comfort</td><td rowspan="2">1900</td><td>0.40</td></tr>
<tr><td>Vulnerability of materials</td><td>0.40</td></tr>
<tr><td colspan="2">State of conservation</td><td>Good</td><td>0.00</td></tr>
<tr><td colspan="2">Primary use</td><td>Residential</td><td>0.82</td></tr>
<tr><td colspan="2">Level of protection</td><td>Medium / Typological</td><td>0.59</td></tr>
</table>

Gategory 5	ID. 182	Loteria street, nº1

<table>
<tr><th colspan="2">Indicator</th><th>Value</th><th>Weight</th></tr>
<tr><td colspan="2">Solar radiation</td><td>0.76</td><td>0.58</td></tr>
<tr><td colspan="2">Acoustic pollution</td><td>64.21 dBA</td><td>0.97</td></tr>
<tr><td colspan="2">Population density</td><td>0.022</td><td>0.29</td></tr>
<tr><td rowspan="2">Date of construction</td><td>Thermal comfort</td><td rowspan="2">1900</td><td>0.40</td></tr>
<tr><td>Vulnerability of materials</td><td>0.40</td></tr>
<tr><td colspan="2">State of conservation</td><td>Fair</td><td>0.00</td></tr>
<tr><td colspan="2">Primary use</td><td>Residential</td><td>0.82</td></tr>
<tr><td colspan="2">Level of protection</td><td>Medium / Typological</td><td>0.59</td></tr>
</table>

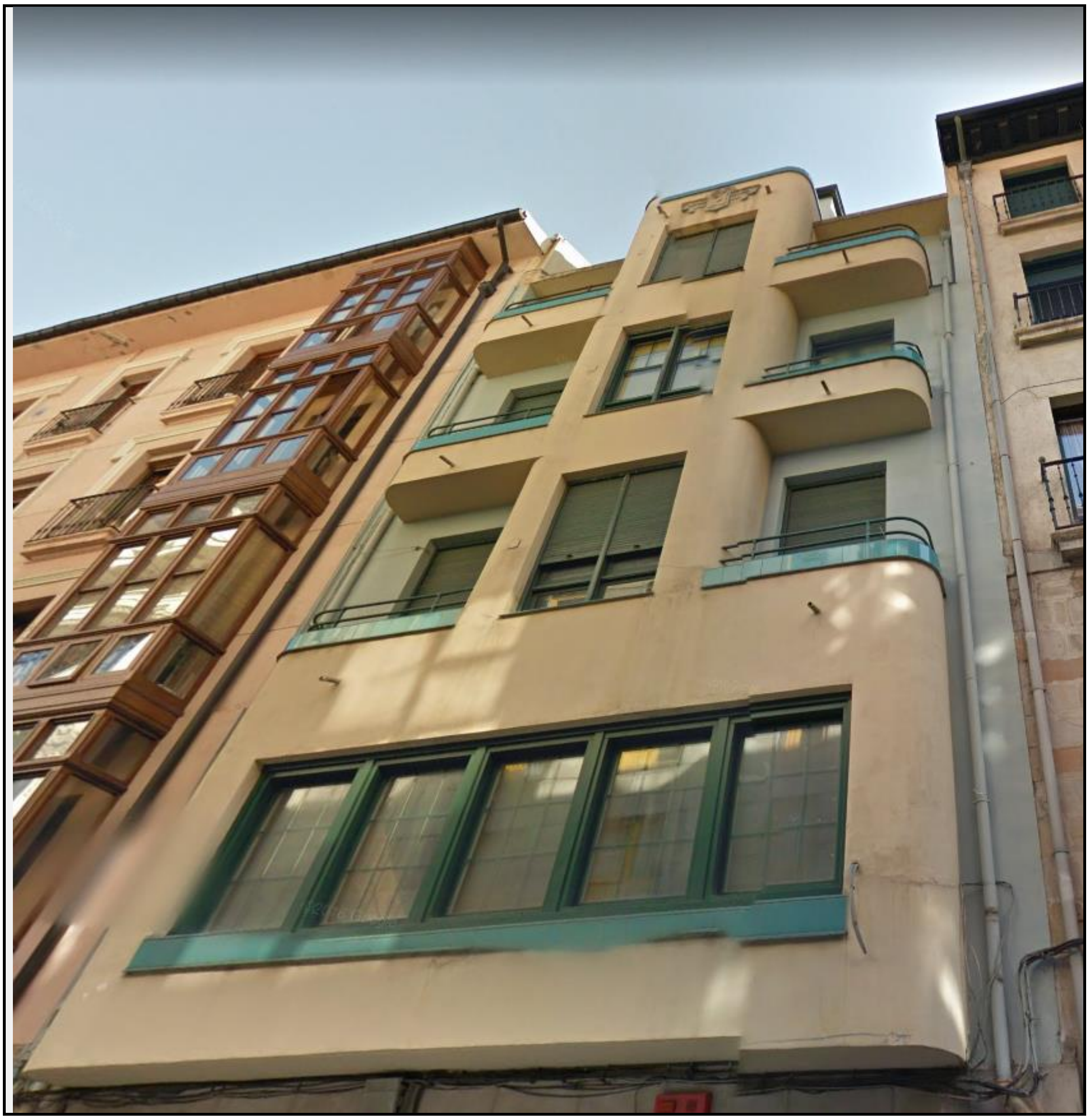
Category 6	ID. 205	Santa Maria street, nº18

Indicator		**Value**	**Weight**
Solar radiation		0.84	**0.70**
Acoustic pollution		61.72 dBA	**0.95**
Population density		0.006	**0.04**
Date of construction	Thermal comfort	1901	**0.40**
	Vulnerability of materials		**0.40**
State of conservation		Fair	**0.36**
Primary use		Residential	**0.82**
Level of protection		Integral	**0.81**

Category 7	ID. 509	Santa Maria street, nº18

Indicator		**Value**	**Weight**
Solar radiation		0.81	**0.66**
Acoustic pollution		48.4 dBA	**0.00**
Population density		0.013	**0.15**
Date of construction	Thermal comfort	1942	**0.40**
	Vulnerability of materials		**0.40**
State of conservation		Good	**0.00**
Primary use		Residential	**0.82**
Level of protection		No protection	**0.00**

Category 8	ID. 129	Santa Maria street, nº5



Indicator		**Value**	**Weight**
Solar radiation		0.78	**0.61**
Acoustic pollution		62.73 dBA	**0.97**
Population density		0.011	**0.10**
Date of construction	Thermal comfort	1930	**0.60**
	Vulnerability of materials		**0.60**
State of conservation		Good	**0.00**
Primary use		Residential	**0.82**
Level of protection		Basic / Ambiental	**0.28**

Category 9	ID. 162	Jardines street, nº1

<table>
<tr><th colspan="2">Indicator</th><th>Value</th><th>Weight</th></tr>
<tr><td colspan="2">Solar radiation</td><td>0.85</td><td>0.73</td></tr>
<tr><td colspan="2">Acoustic pollution</td><td>63.73 dBA</td><td>0.97</td></tr>
<tr><td colspan="2">Population density</td><td>0.014</td><td>0.15</td></tr>
<tr><td rowspan="2">Date of construction</td><td>Thermal comfort</td><td rowspan="2">1950</td><td>0.60</td></tr>
<tr><td>Vulnerability of materials</td><td>0.60</td></tr>
<tr><td colspan="2">State of conservation</td><td>Good</td><td>0.00</td></tr>
<tr><td colspan="2">Primary use</td><td>Residential</td><td>0.82</td></tr>
<tr><td colspan="2">Level of protection</td><td>Medium / Typological</td><td>0.59</td></tr>
</table>

For the calculation of the vulnerability, the categories are completed with the information from each sample building to apply the previously developed MIVES weights and values, as shown in Table 68.

	Vulnerability								
	Sensitivity							CC	
	0.82							0.18	
	Environmental		Social		Physical		Economic	Cultural	
	0.37		0.28		0.22		0.13	100	
	Solar rad.	Acoustic pollution	Pop. density	Date of const. T.	Date of const. V.	State of cons.	Use	Protecti on level	
	0.76	0.24	0.24	0.76	0.47	0.53	1.00	1.00	
C1	0.68	0.97	**0.12**	0.40	0.40	0.00	0.82	0.59	V2
C2	0.66	0.00	**0.13**	0.40	0.40	0.00	0.82	0.59	V1
C3	0.64	0.95	**0.31**	0.40	0.40	0.00	0.82	0.28	V1
C4	0.61	0.97	**0.00**	0.40	0.40	0.00	0.82	0.59	V2
C5	0.58	0.97	**0.29**	0.40	0.40	0.00	0.82	0.59	V2
C6	0.7	0.95	**0.04**	0.40	0.40	0.36	0.82	0.81	V1
C7	0.66	0.00	**0.15**	0.40	0.40	0.00	0.82	0.00	V1
C8	0.61	0.97	**0.10**	0.60	0.60	0.00	0.82	0.28	V1
C9	0.73	0.97	**0.15**	0.60	0.60	0.00	0.82	0.59	V3

Table 68. Vulnerability of categories of buildings.

Once the vulnerability for the sample buildings is stablished, the results can be extrapolated to the categorized building within the area. The next figure (Figure 60) shows the extrapolation of the categories vulnerability to the buildings belonging to the same category. Ending, as a result with all of the categorized buildings within the area having an associated vulnerability level. This is shown on Figure 60, the ones remaining in grey are the buildings that did not fit into the categorization.

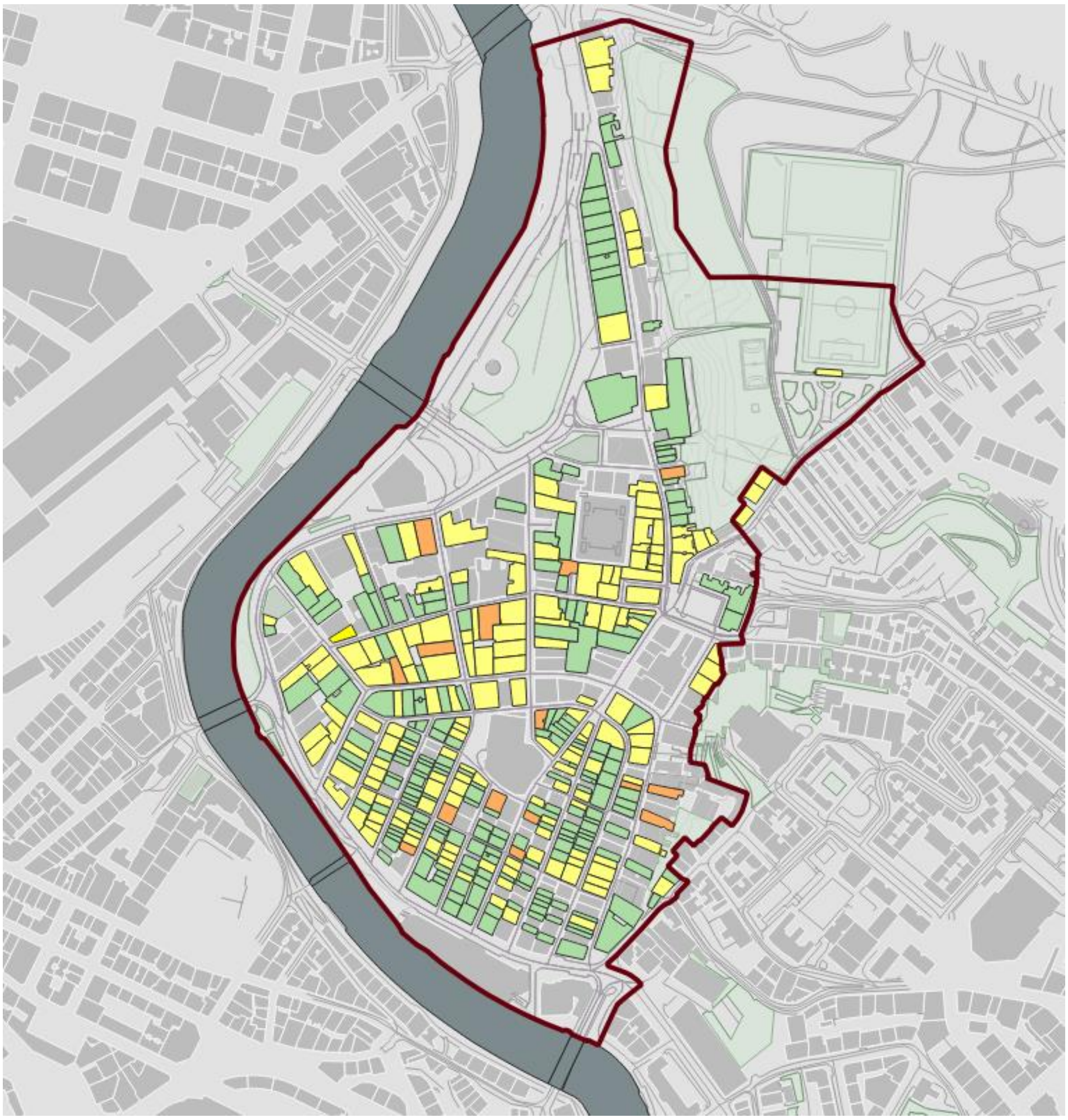


Figure 60. Vulnerability of buildings according to the categories for Bilbao.

Sample Public spaces

Category 1	ID. 18	Arriaga square

Indicator	Value	Weight
NDVI	0.02	0.97
SVF	0.77	0.45
Solar radiation	0.65	0.41
Relevance	5.00	0.59
Accessibility	1.00	0.00

Category 2	ID. 14	Calle de la Rivera street

Indicator	Value	Weight
NDVI	0.14	0.79
SVF	0.71	0.36
Solar radiation	0.65	0.41
Relevance	11.00	0.90
Accessibility	1.00	0.00

Category 3	ID. 22	San Nicolas square

Indicator	Value	Weight
NDVI	0.08	0.88
SVF	0.54	0.15
Solar radiation	0.59	0.33
Relevance	0.00	0.00
Accessibility	1.00	0.00

Category 4	ID. 38	Calle de la Rivera street

Indicator	Value	Weight
NDVI	0.06	0.91
SVF	0.19	0.01
Solar radiation	0.36	0.11
Relevance	5.00	0.59
Accessibility	1.00	0.00

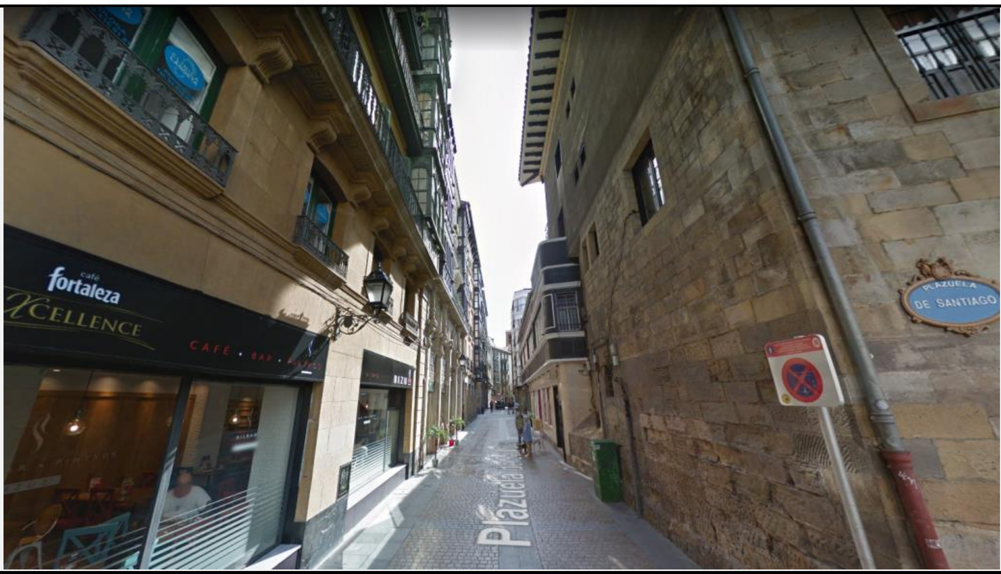
Category 5	ID. 77	San Nicolas square

Indicator	**Value**	**Weight**
NDVI	0.15	0.77
SVF	0.23	0.01
Solar radiation	0.32	0.09
Relevance	14.00	0.98
Accessibility	1.00	0.00

Category 6	ID. 34	Calle de la Rivera street

Indicator	**Value**	**Weight**
NDVI	0.12	0.82
SVF	0.19	0.01
Solar radiation	0.29	0.07
Relevance	16.00	1.00
Accessibility	1.00	0.00

Category 7	ID.84	Plazuela de Santiago



Indicator	Value	Weight
NDVI	0.11	0.83
SVF	0.14	0.00
Solar radiation	0.50	0.23
Relevance	4.00	0.51
Accessibility	4.98	0.01

Category 8	ID. 43	Santa Maria street

Indicator	Value	Weight
NDVI	0.08	0.88
SVF	0.21	0.01
Solar radiation	0.40	0.14
Relevance	8.00	0.78
Accessibility	1.00	0.00

Category 9	ID.54	Carniceria vieja street

Indicator	Value	Weight
NDVI	0.11	0.83
SVF	0.16	0.00
Solar radiation	0.43	0.17
Relevance	29.00	1.00
Accessibility	5.60	0.00

Category 10	ID. 34	Alejandro de la Sola street

Indicator	Value	Weight
NDVI	0.14	0.82
SVF	0.08	0.00
Solar radiation	0.82	0.67
Relevance	0.00	0.00
Accessibility	2.74	0.65

For the calculation of the vulnerability, MIVES methodology is applied to the categories, as shown in Table 69.

	Vulnerability					
Requirement	Sensitivity				CC	
Weight	0.87				0.13	
Criteria	Physical		Environmental	Socio/Cultural Economic	Accessibility	
Weight	0.36		0.32	0.31	1.00	
Indicator	NDVI	SVF	Solar radiation	Relevance	Accessibility	
Weight	0.48	0.52	1.00	1.00	1.00	
C1	0.97	0.45	0.41	0.59	0.00	V1
C2	0.79	0.36	0.41	0.90	0.00	V1
C3	0.88	0.15	0.33	0.00	0.00	V1
C4	0.91	0.01	0.11	0.59	0.00	V1
C5	0.77	0.01	0.09	0.98	0.00	V1
C6	0.82	0.01	0.07	1.00	0.00	V1
C7	0.83	0.00	0.23	0.51	0.01	V1
C8	0.88	0.01	0.14	0.78	0.00	V1
C9	0.83	0.00	0.17	1.00	0.00	V1
C10	0.82	0.00	0.67	0.00	0.65	V1

Table 69. Vulnerability of categories of public spaces of the case study of Bilbao.

The next figure (Figure 61) shows the extrapolation of the categories vulnerability to the public spaces belonging to the same category. As they all belong to the same vulnerability level, the results are not very relevant.

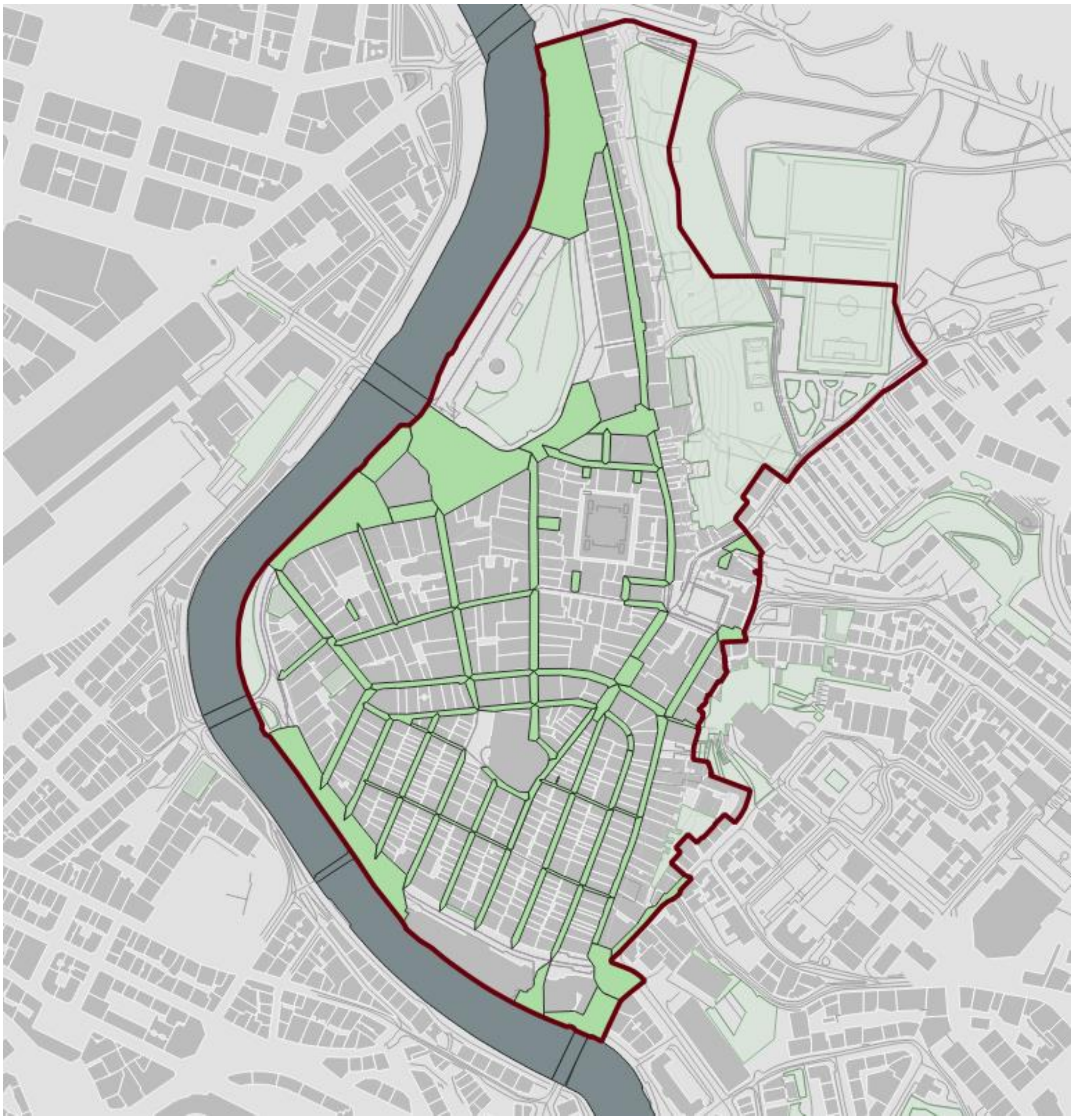


Figure 61. Results of the vulnerability assessment for the open spaces using the categorization process.

4.4 Vulnerability assessment

In this section, the vulnerability assessment using the full methodology will be shown. In this case, all of the elements will be assessed individually to compare with the categorization method and assess the results. As previously mentioned, in the case of Bilbao, because of the limitations in data availability some indicators could not be used, namely, vulnerable population, the link to historical events and the presence of the elevator in the case of buildings, and albedo, air pollution and the link to historical events in the case to public spaces. To ensure the replicability of the methodology, those indicators have been excluded from the decision tree and the vulnerability index is obtained maintaining the proportion of the weights as explained in chapter 3 (Table 70)

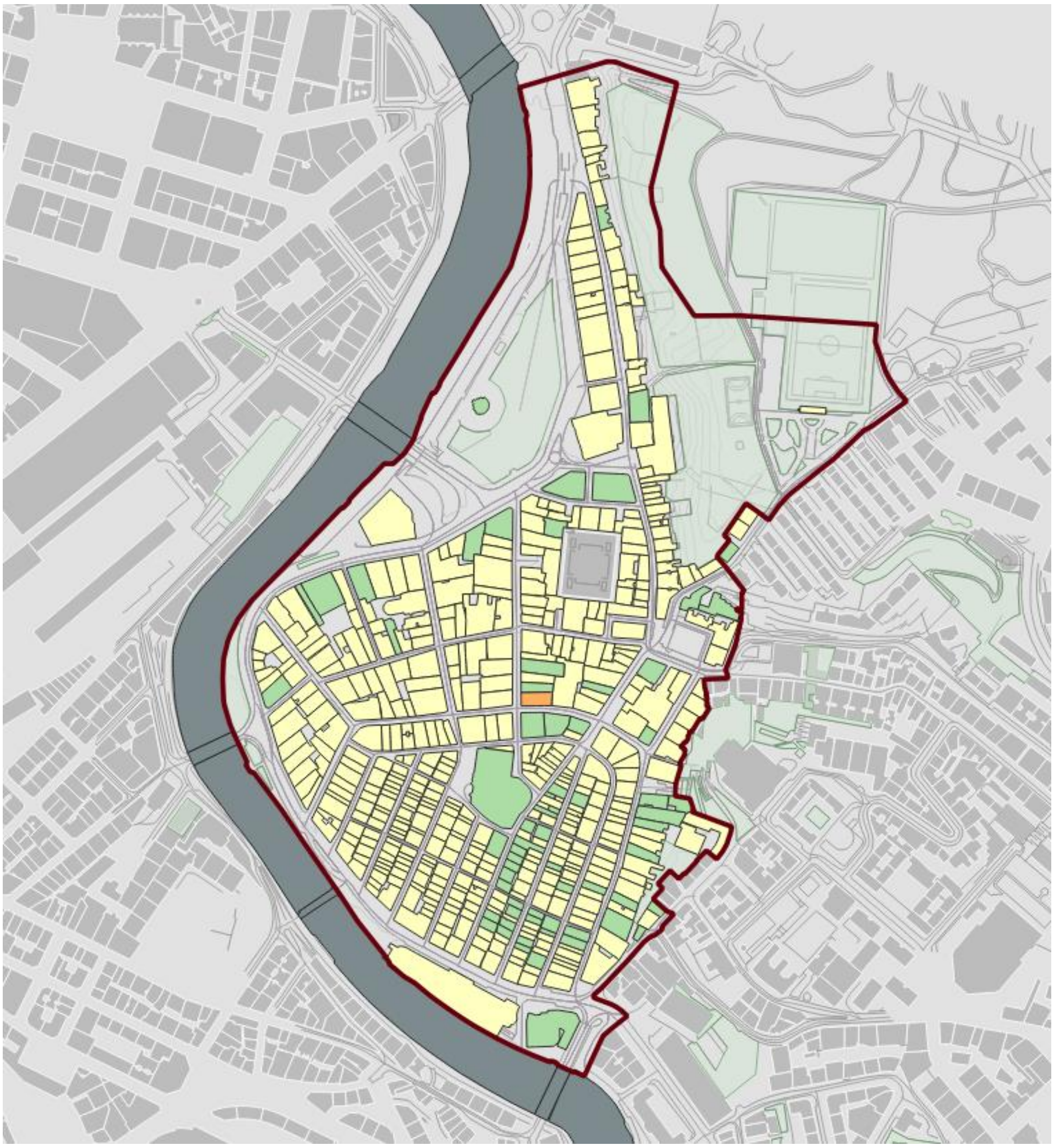
Req	Criteria weight	Criteria	Indicator weight	Indicator	Indicator class	Range	VALUES
Sensitivity	0.37	Environmental	0.76	Solar radiation	**Shadow fraction**		**VALUES**
					very low	<0.2	0.00
					low	0.2 to 0.4	0.20
					medium	0.4-0.7	0.60
					high	0.7-1	1.00
			0.24	Acoustic pollution	**Environmental**		**VALUES**
					low	< 50 dBA	0.00
					medium	50 dBA to 70dBA	0.54
					high	> 70 dBA	1.00
	0.28	Social sensitivity	0.24	Population density	**Inhabitants per sqm of residential area in the building**		**VALUES**
					Empty	0	0.00
					Low	x<0.02 habs/m2	0.26
					medium	0.02 < x < 0.05 habs/m2	0.61
					high	0.05 < x habs/m2	1.00
			0.76	Date of construction (thermal comfort)	**Date of construction**		**VALUES**
					>2006		0.00
					1970<x2006		0.40
					1920<x<1970		0.69
					XVI<x<1920		0.56
					<XVI century		1.00
	0.22	Physical	0.47	Date of construction (linked to vulnerability of materials)	**Date of construction**		**VALUES**
					>2006		0.00
					1920<x2006		0.40
					1850<x<1920		0.69
					XVI<x<1850		0.56
					<XVI century		1.00
			0.53	State of conservation	**State of conservation**		**VALUES**
					Good		0.00
					Fair		0.36
					Bad		0.77
					Very bad /ruin		1.00
	0.13	Economic	1	Primary use	**Primary use**		**VALUES**
					Residential		0.82
					Industrial		0.48
					Public use (social/cultural)		0.84
					Touristic		0.43
CC	1	Cultural value	1.00	Level of protection	**Protection level of the building**		**VALUES**
					None	None	0.00
					Low	Basic / ambient	0.28
					medium	Typological	0.59
					high	Integral	0.81
					Very high	Monument	1.00

Table 70. Final decision tree and relative weight for the vulnerability index for the case study of Bilbao.

Req	Criteria weight	Criteria	Indicator weight	Indicator	Class	Range	VALUES
Sensitivity	0.36	Physical	0.48	NDVI	**Normalized Difference Vegetation Index**		VALUES
					low	x < 0.2	0.00
					medium	0.2 < x < 0.5	0.35
					high	0.5 < x	1.00
			0.52	SVF	**Sky view Factor**		VALUES
					Very high	> 0.65	0.00
					high	0.5 to 0.65	0.20
					medium	0.35 to 0.5	0.80
					low	< 0.35	1.00
	0.33	Environmental	1.00	Solar radiation	**Shadow fraction**		VALUES
					very low	<0.2	0.00
					low	0.2-0.4	0.20
					medium	0.4-0.7	0.80
					high	0.7-1	1.00
	0.31	Socio-Cultural	1.00	Relevance to life (GF commercial activities on buildings)	**GF commercial activities on buildings per 100m street / square**		VALUES
					low	Less than 5	0.00
					medium	Between 5 and 15	0.57
					high	More than 15	1.00
Coping capacity	1.00	Accesibility of urban grid	1.00	Accesible for ambulances / firefighter	**Accesibility for ambulances or firefighters (according to local regulations)**		VALUES
					good		1.00
					bad		0.70
					None		0.00

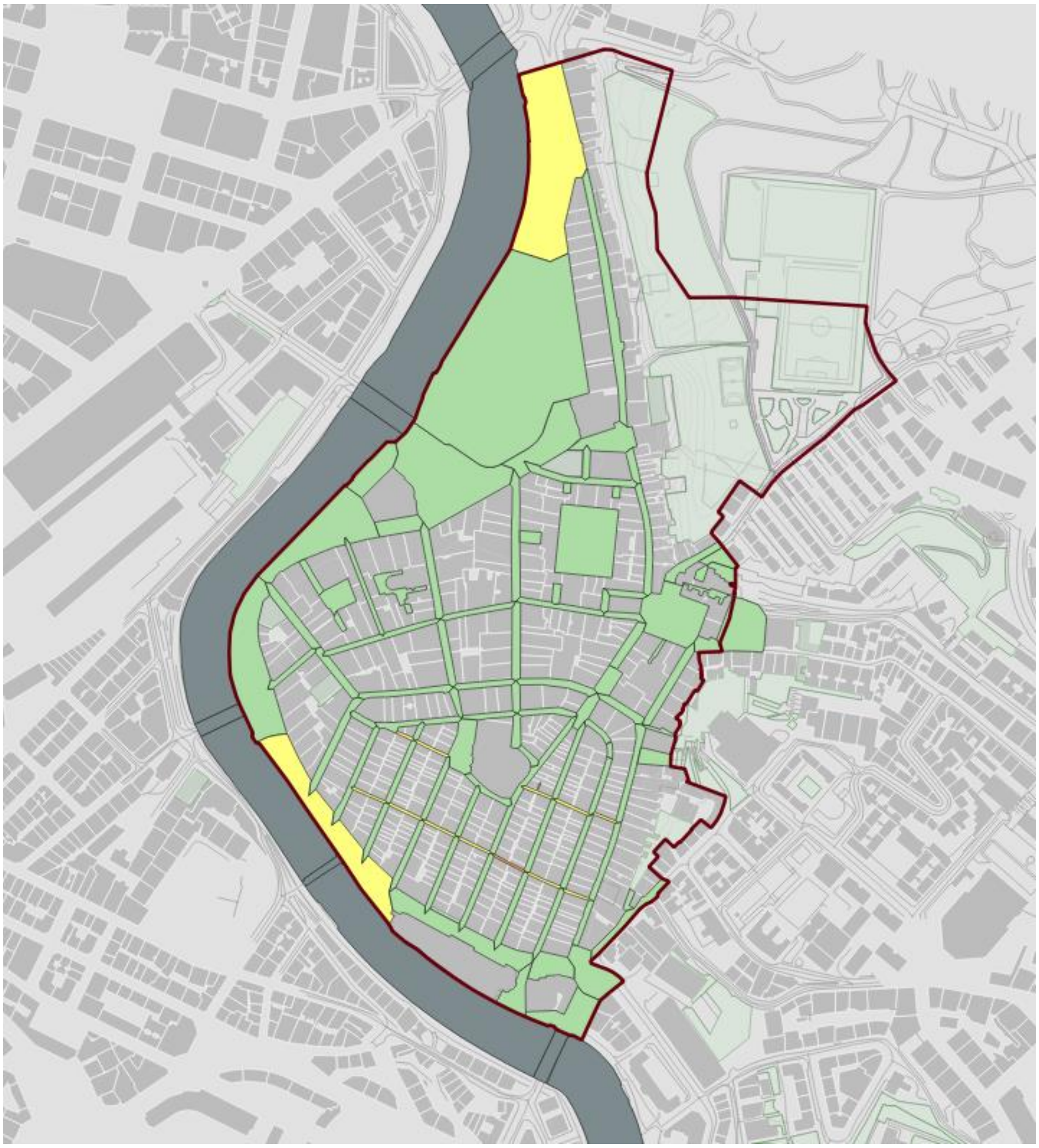
Table 71. Weights of the public spaces requirement tree.

The values and weights calculated in the previous chapter are applied to the semantic information gathered in the model, providing as a result the sensitivity and coping capacity of every element under assessment. As was described in chapter 3, the vulnerability is composed by a sensitivity index and a coping capacity index. The results for both buildings and public spaces are shown from Figure 62 to Figure 65.



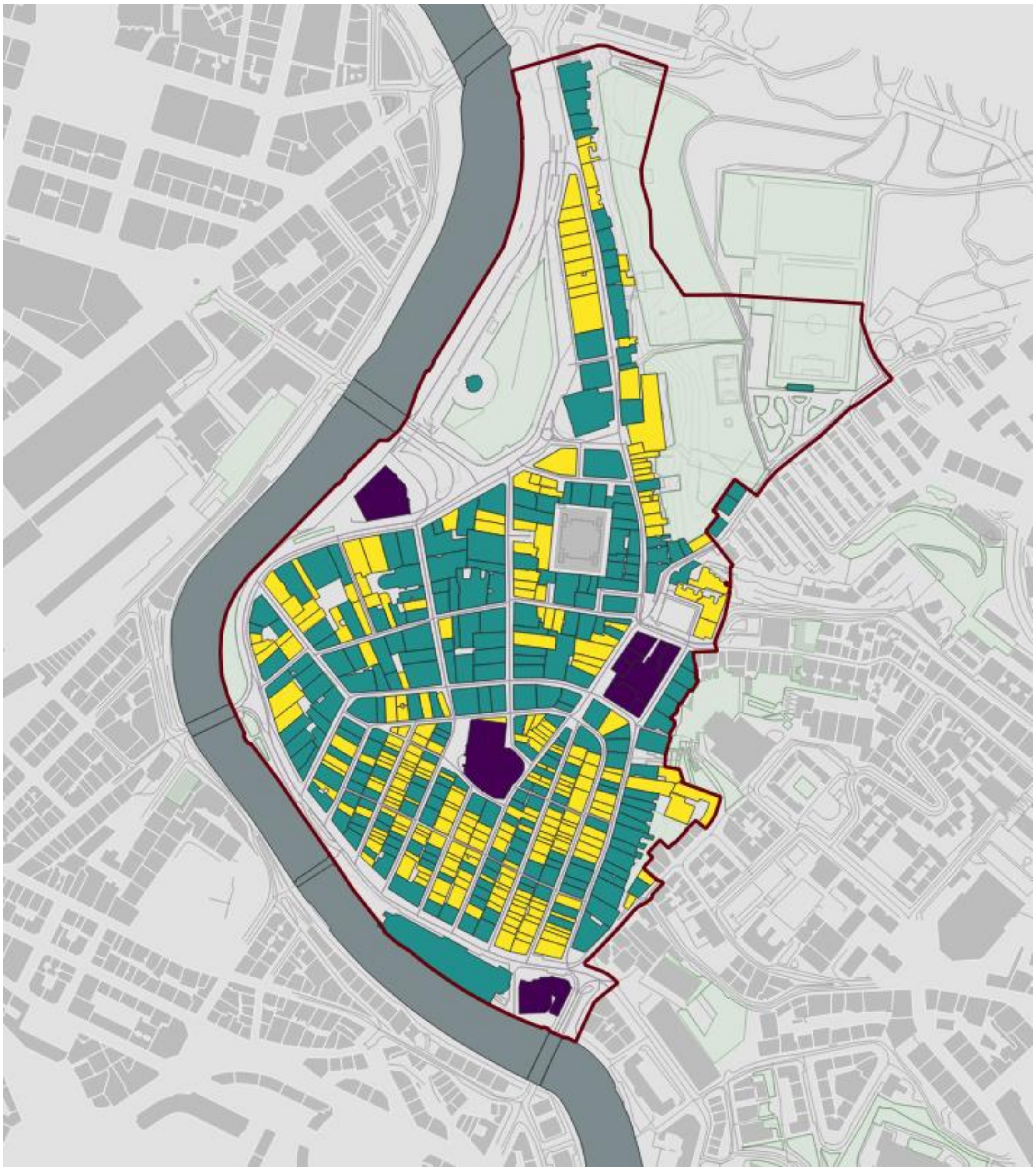
$S_B0 \leq 0.10$	
$0.10 < S_B1 \leq 0.40$	
$0.40 < S_B2 \leq 0.60$	
$0.60 < S_B3 \leq 0.80$	
$0.90 < S_B4 \leq 1.00$	

Figure 62. Sensitivity of buildings for Bilbao.



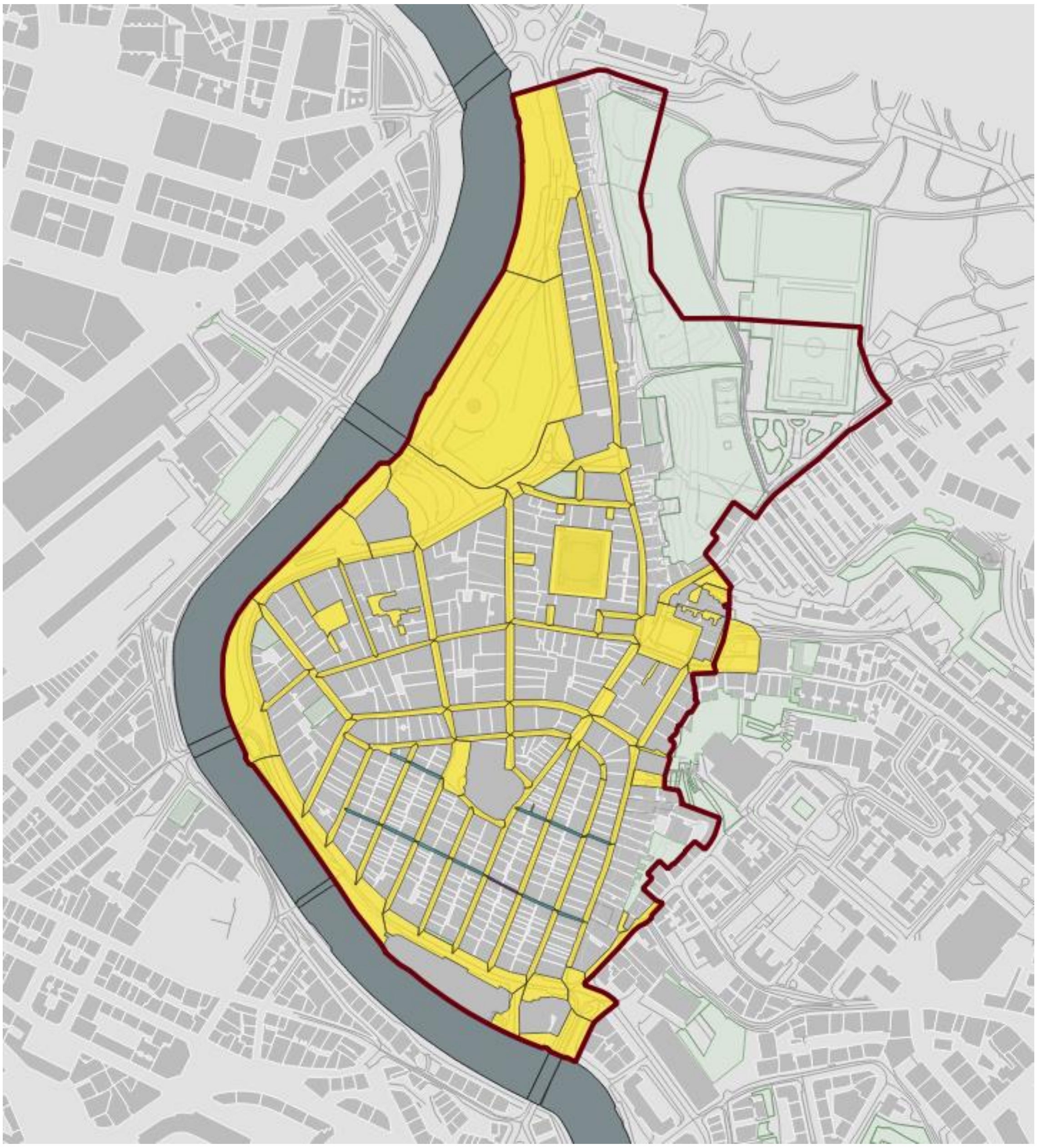
$\mathbf{S_B0} \leq 0.10$	
$0.10 < \mathbf{S_B1} \leq 0.40$	
$0.40 < \mathbf{S_B2} \leq 0.60$	
$0.60 < \mathbf{S_B3} \leq 0.80$	
$0.90 < \mathbf{S_B4} \leq 1.00$	

Figure 63. Sensitivity of public spaces for Bilbao.



$\mathbf{CC_{B}0} \leq 0.33$	
$0.33 < \mathbf{CC_{B}1} \leq 0.75$	
$0.75 < \mathbf{CC_{B}2} \leq 1.00$	

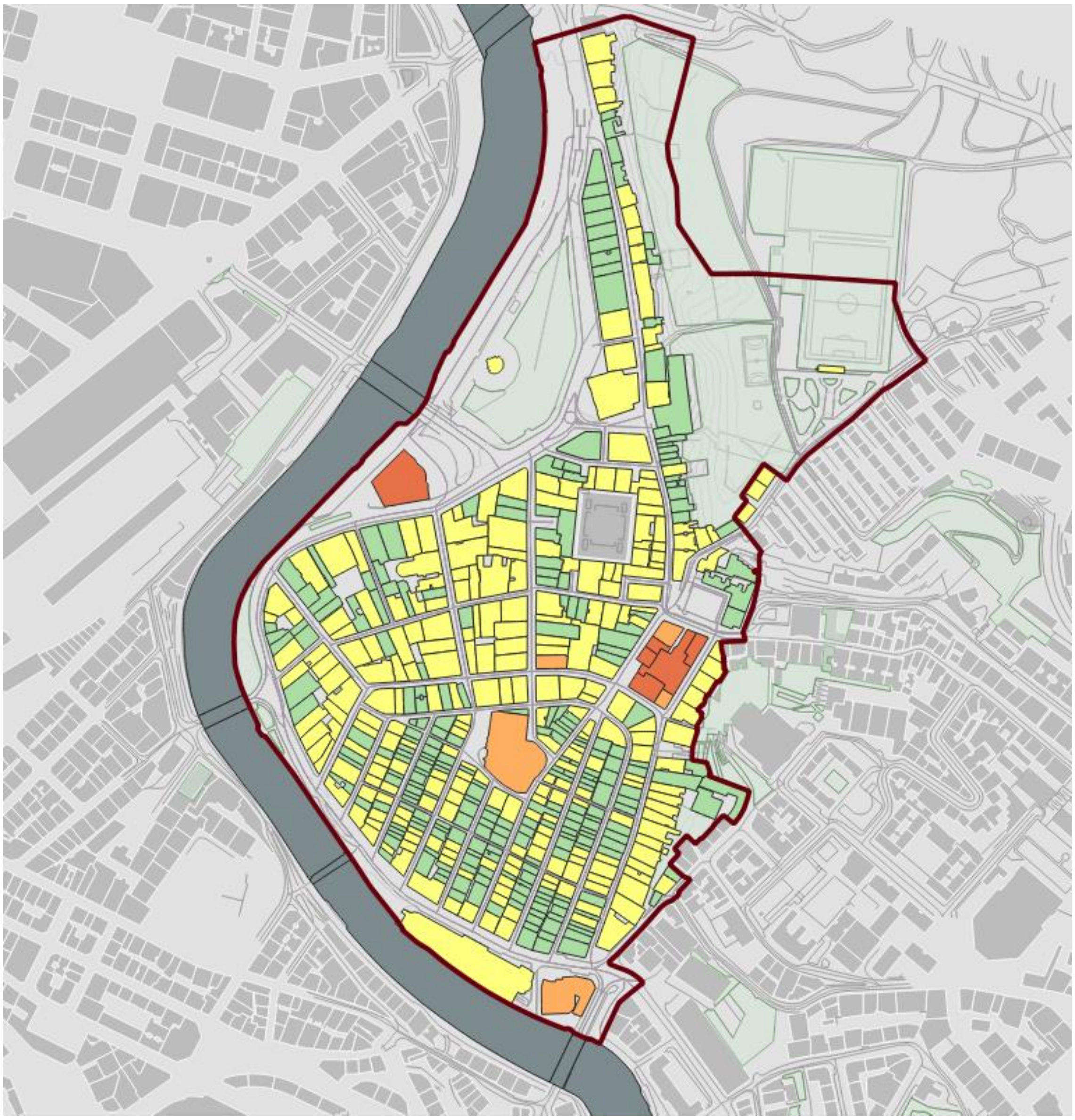
Figure 64. Coping capacity for buildings in Bilbao.



$\mathbf{CC_B0} \leq 0.33$	
$0.33 < \mathbf{CC_B1} \leq 0.75$	
$0.75 < \mathbf{CC_B2} \leq 1.00$	

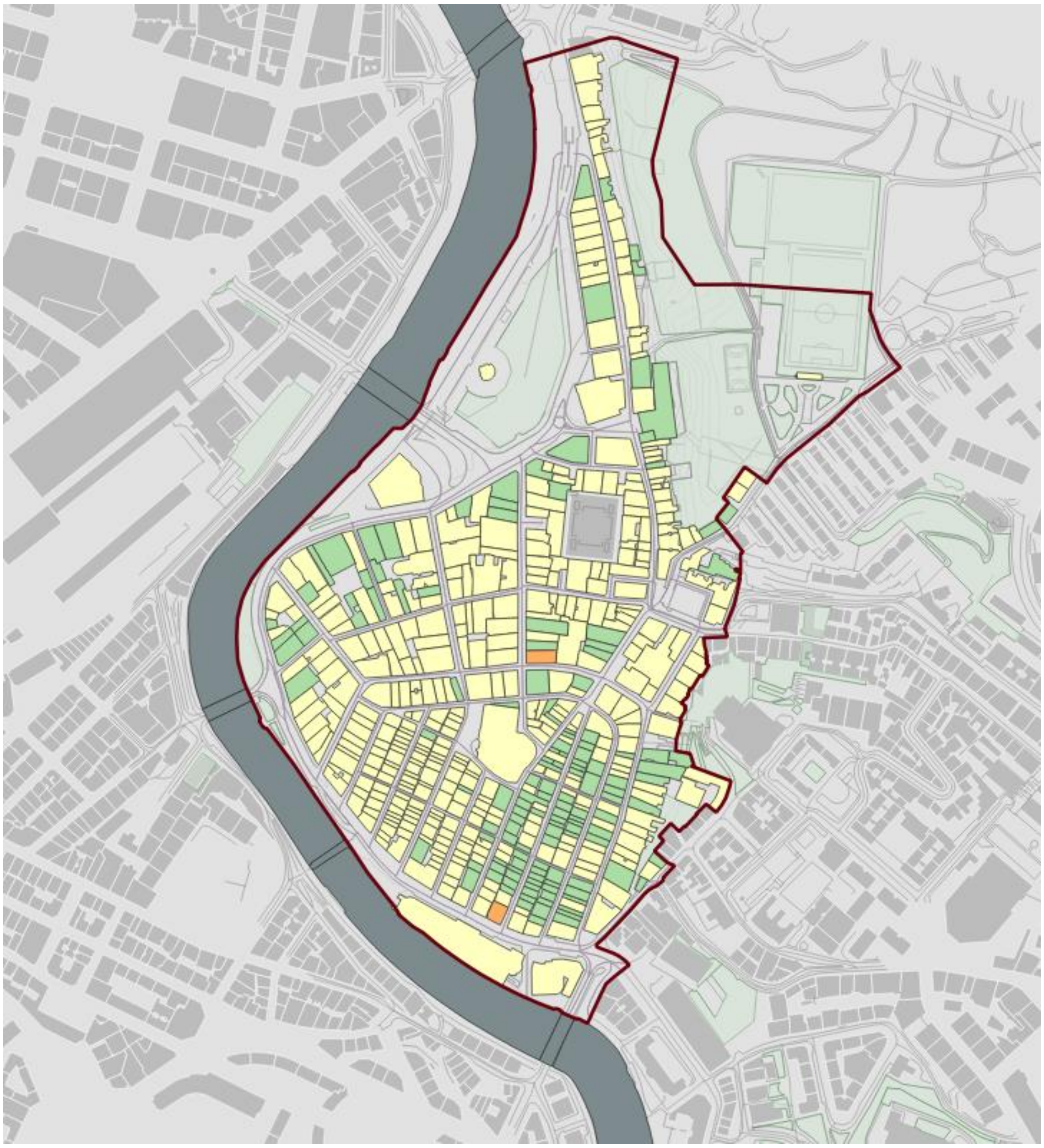
Figure 65. Coping capacity for public spaces in Bilbao.

Vulnerability has different levels according to the sensitivity and coping capacity of the element, from V0 to V5.



		Sensitivity: low to high				
		S0	S1	S2	S3	S4
Lack of coping capacity: low to high	CC0	V_B0	V_B1	V_B1	V_B2	V_B3
	CC1	V_B1	V_B2	V_B2	V_B3	V_B4
	CC2	V_B2	V_B3	V_B4	V_B5	V_B5

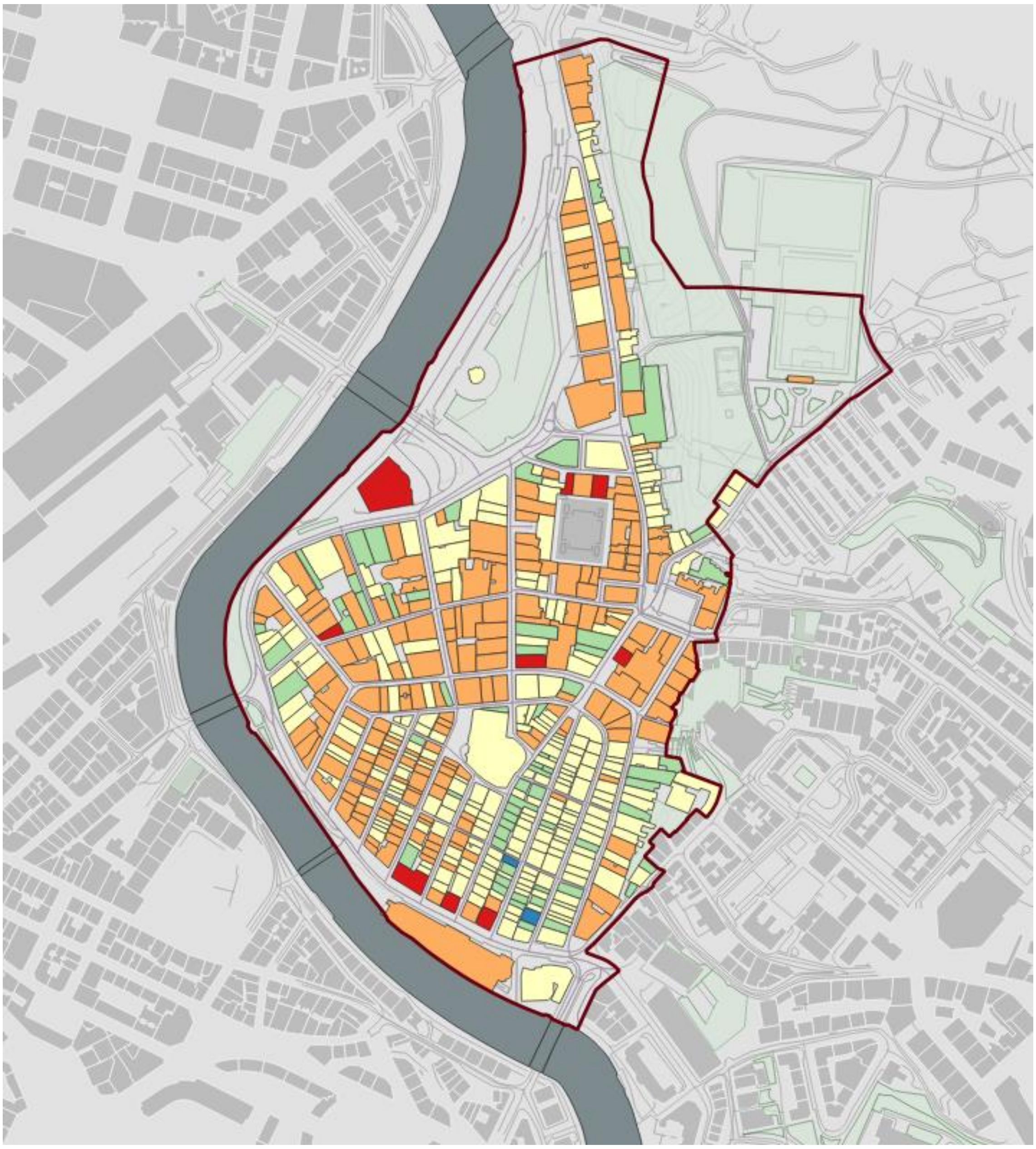
Figure 66. Vulnerability for buildings in Bilbao according to the index.



$\mathbf{V_B0} \leq 0.10$	
$0.10 < \mathbf{V_B1} \leq 0.40$	
$0.40 < \mathbf{V_B2} \leq 0.60$	
$0.60 < \mathbf{V_B3} \leq 0.80$	
$0.90 < \mathbf{V_B4} \leq 1.00$	

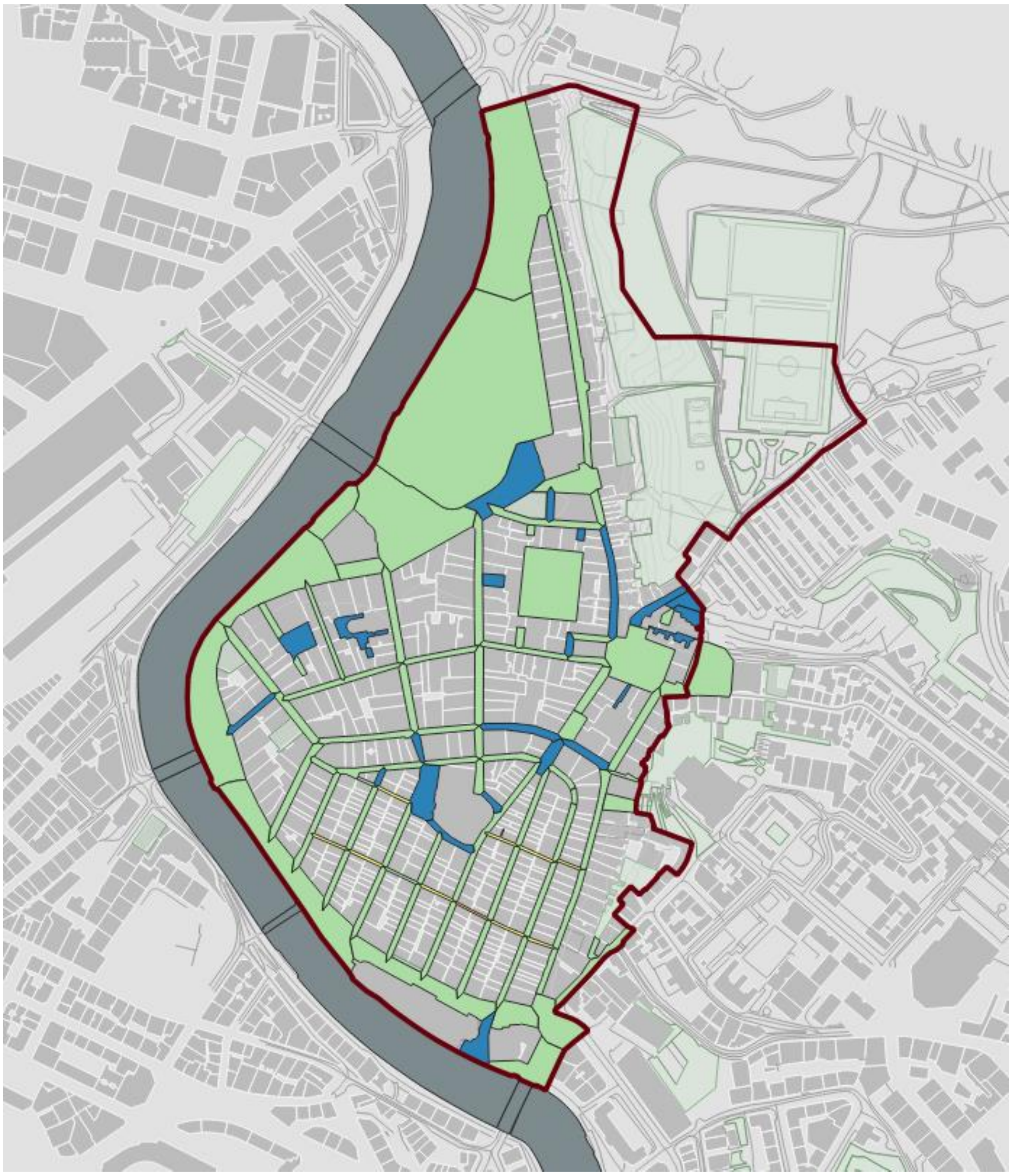
Figure 67. Vulnerability of buildings for Bilbao using a numerical range.

The values for the vulnerability of buildings present a minimum of 0.16 to a maximum of 0.66. For a more accurate representation of results, the visualization is modified readjusting the range using this values as minimum and maximum and dividing the in between values equally as shown on Figure 68.



$0.16 < \mathbf{V_B0} \leq 0.26$	
$0.26 < \mathbf{V_B1} \leq 0.36$	
$0.36 < \mathbf{V_B2} \leq 0.46$	
$0.46 < \mathbf{V_B3} \leq 0.56$	
$0.56 < \mathbf{V_B4} \leq 0.66$	

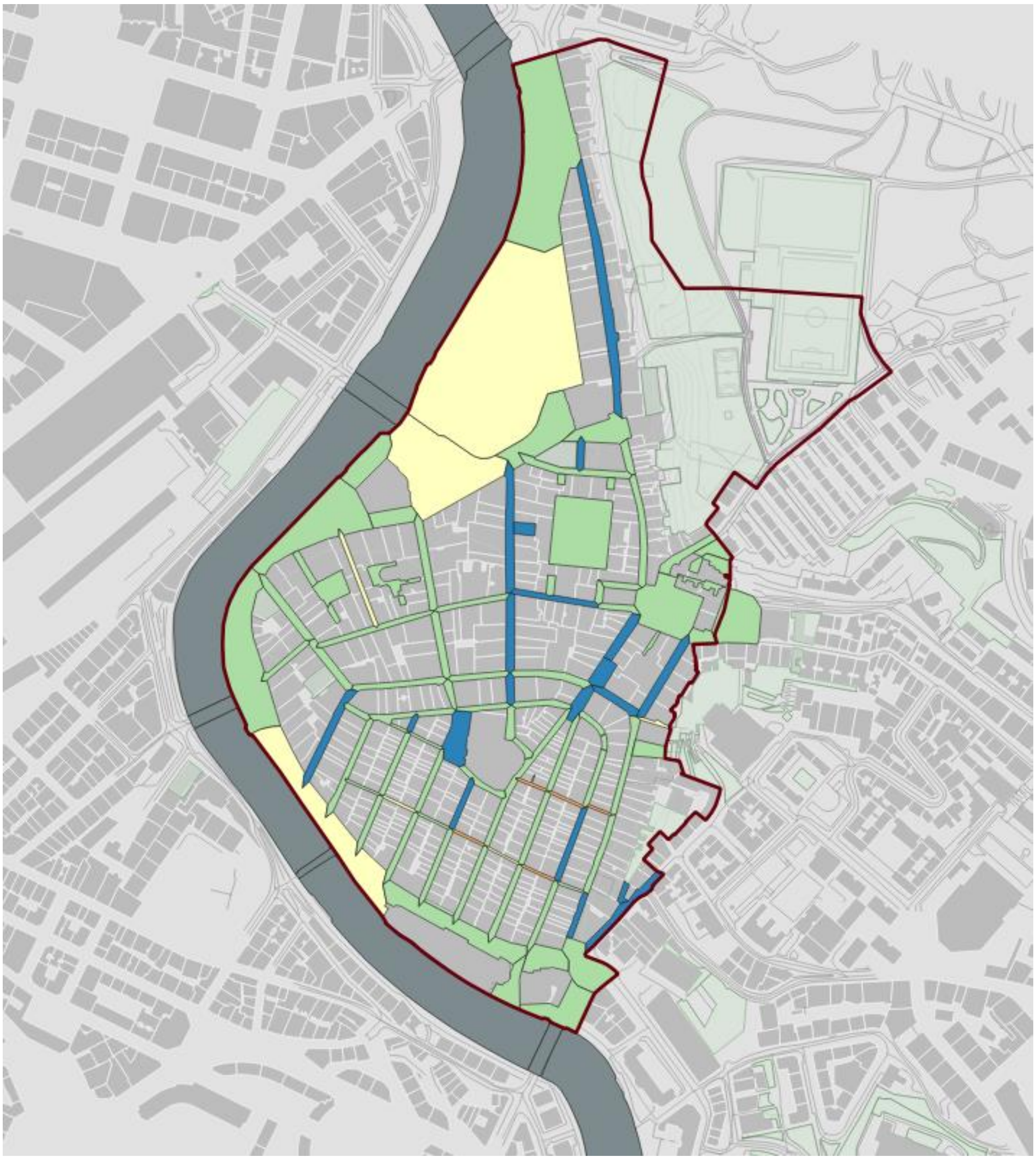
Figure 68. Vulnerability of buildings in Bilbao adjusting the values to minimum and maximum.



Lack of coping capacity: low to high		Sensitivity: low to high				
		S0	S1	S2	S3	S4
	CC0	V_B0	V_B1	V_B1	V_B2	V_B3
	CC1	V_B1	V_B2	V_B2	V_B3	V_B4
	CC2	V_B2	V_B3	V_B4	V_B5	V_B5

Figure 69. Vulnerability for public spaces in Bilbao according to index.

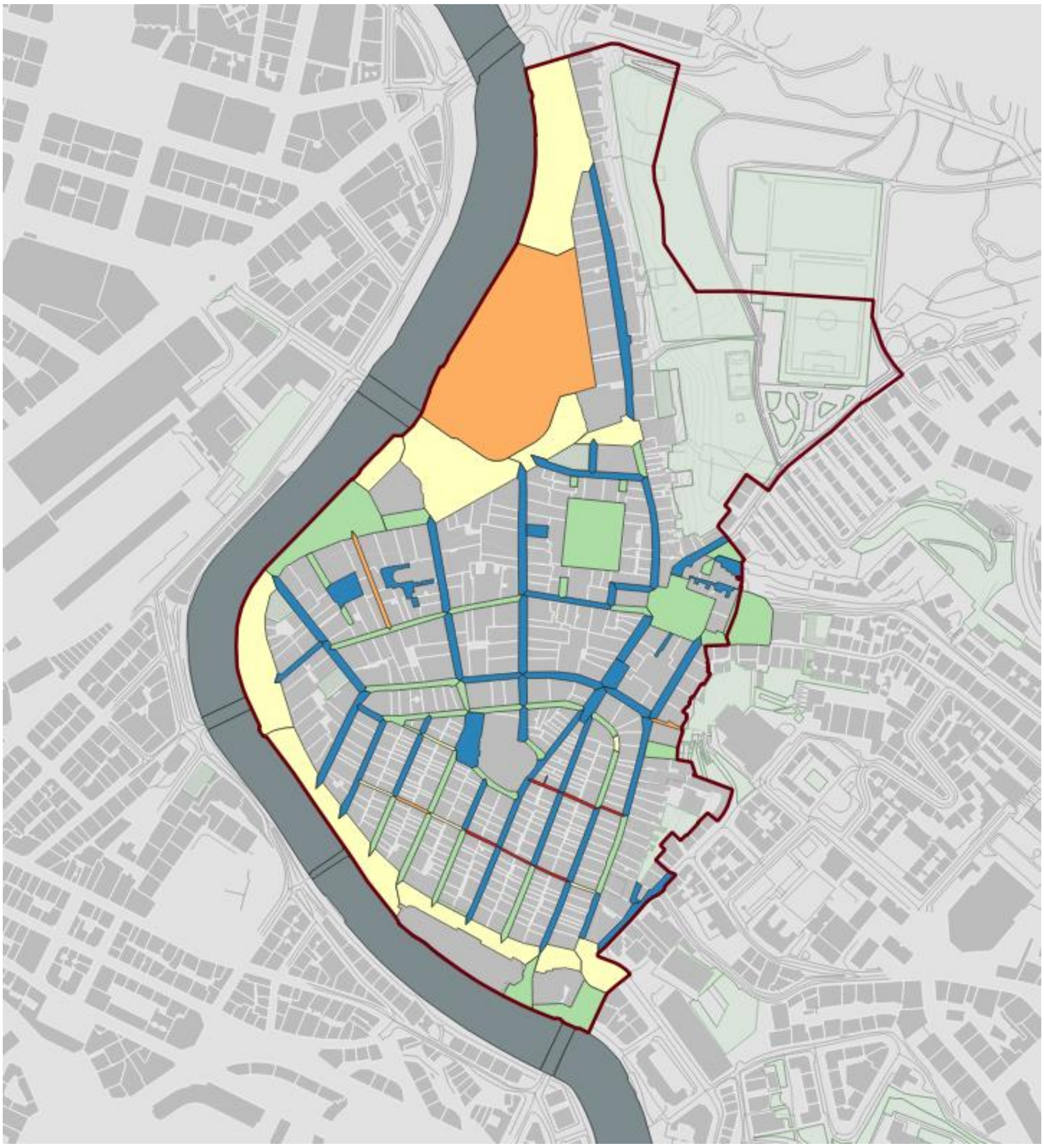
As for the buildings, the representation using a numerical range is as follows:



$\mathbf{V_{B}0} \leq 0.10$	
$0.10 < \mathbf{V_{B}1} \leq 0.40$	
$0.40 < \mathbf{V_{B}2} \leq 0.60$	
$0.60 < \mathbf{V_{B}3} \leq 0.80$	
$0.90 < \mathbf{V_{B}4} \leq 1.00$	

Figure 70. Vulnerability of public spaces in Bilbao using a numerical range.

The minimal value for vulnerability of a public space is 0.04 and the highest 0,69.adjustin the visualization to use this values as minimum and maximum and adjustin the ranges, the results are as follows:



$0.04 < \mathbf{V_{B}0} \leq 0.17$	
$0.17 < \mathbf{V_{B}1} \leq 0.30$	
$0.30 < \mathbf{V_{B}2} \leq 0.43$	
$0.43 < \mathbf{V_{B}3} \leq 0.56$	
$0.56 < \mathbf{V_{B}4} \leq 0.69$	

Figure 71. Vulnerability of open spaces in Bilbao adjusting the values to minimum and maximum.

4.5 Risk Assessment

4.5.1 Hazard requirement calculation

Following the methodology developed in chapter 3, risk is calculated adding the hazard requirement to the vulnerability. If a denser network of weather stations within the city would have been available, the value would vary depending on the element and the hazard conditions around it, but as there is only one station close to the historic area, the same value applies to every element.

For this, the heat wave of July 2022 was used as an example, as it was one of the most extreme recorded in the area. This heat wave broke the records with a maximum temperature of 40.4°C on the 17th of July. For the calculation of the indicators for the hazard the data from the weather station of Deusto, situated at the extreme northern end of Zorrotzaurre Island, was selected. This station is the one closest to the historic area and measures temperature, relative humidity and wind every 10 minutes and the data is easily accessible through Euskalmet (acronym for the Basque Meteorological Agency).

	Heat wave data 12-18th July 2022				
	Maximum temperature	Thermal shock	RH	RH shocks daily	Duration
12th	31°C	11.6°C	63.9%	2	
13th	36.8°C	16°C	49.9%	2	
14th	32.9°C	14.0°C	55.5%	2	
15th	32.5°C	13.5°C	56.8%	3	
16th	37.7°C	16.4°C	49.4%	2	
17th	40.4°C	17.8°C	45.7%	2	
18th	38.8°C	18.0°C	59%	1	
Average	**35.7°C**	**15.33**	**54.3%**	**2**	**6 days**
Value for each indicator	**0.73**	**0.57**	**0.58**	**0.25**	**1.00**

Table 72. Data for the calculation of the indicators values for the hazard.

The heat wave went on for 6 days, from the 12th to the 18th of July, with maximum temperatures over 31°C every day. The main data for the heat wave indicators is shown on Table 72.

After following the weighting of the criteria for hazards set on chapter 3, the criteria and final weight of the hazard requirement is weighted as shown in Table 73.

	Criteria value	Weight	Hazard weight
Temperature	0.69	0.58	0.71
Relative humidity	0.47	0.19	
Duration	1.00	0.22	

Table 73. Calculation of the weight for the hazard requirement.

4.5.2 Risk assessment

As for vulnerability, two ways of visualizing the final risk score will be provided. A numerical visualization using the results of the assessment and through an index.

For the calculation of the risk index as shown in chapter 3, the levels for the hazard need to be stablished, following three ranges as explained in section 3.3.2:

- **H0** ≤ 0.33
- 0.33 < **H1** ≤ 0.75
- 0.75 < **H2** ≤ 1.00

As shown on Table 61 risk has different levels according to the hazard range and vulnerability of the element, from R0 to R5, as the hazard is the same value for every element under assessment, the index for this case is as shown in Table 74.

		Vulnerability: low to high				
		V0	V1	V2	V3	V4
Hazard	H2	R0	R2	R2	R3	R4

Table 74. Risk levels.

The final results for both buildings and public spaces are shown from Figure 72.

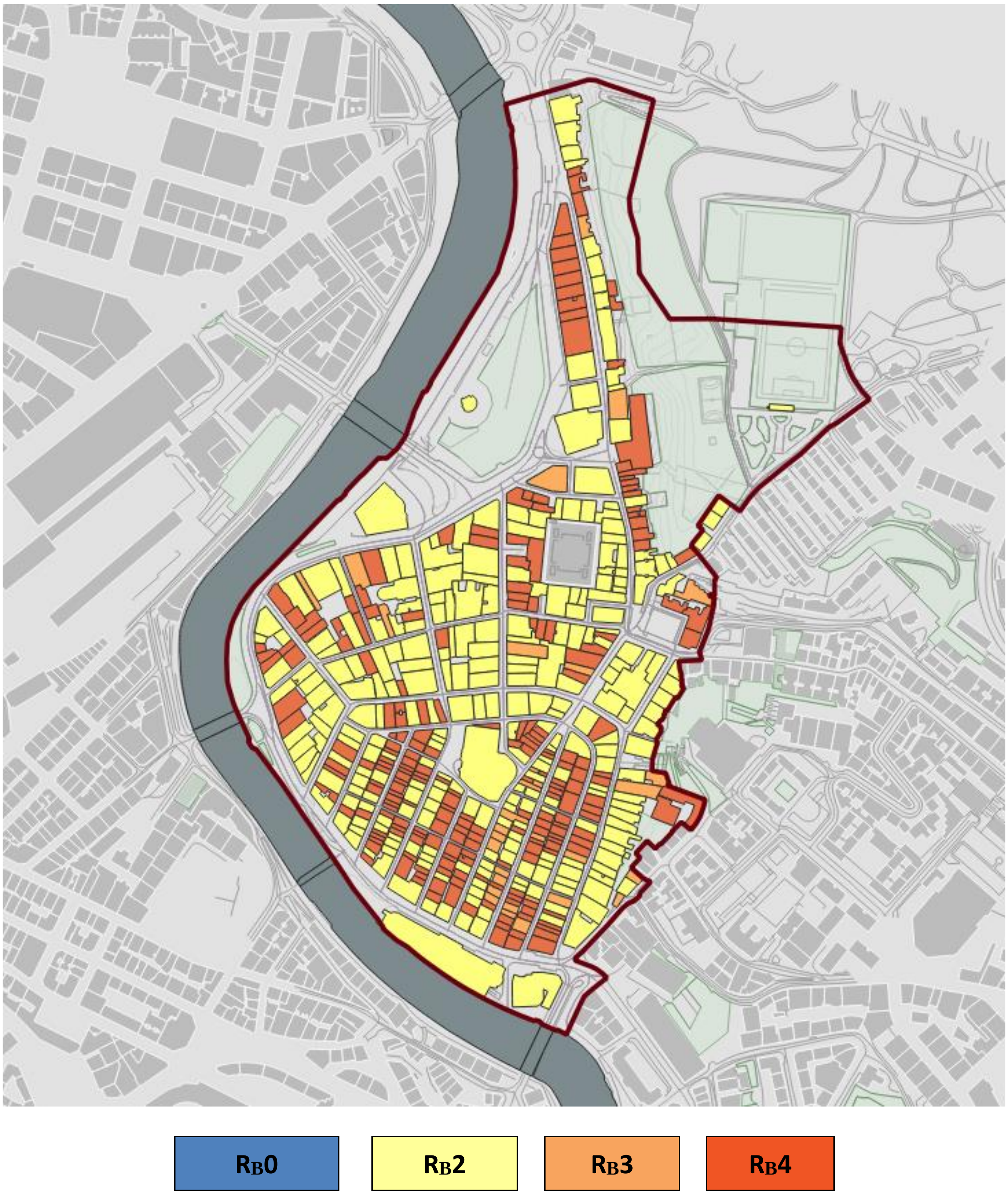
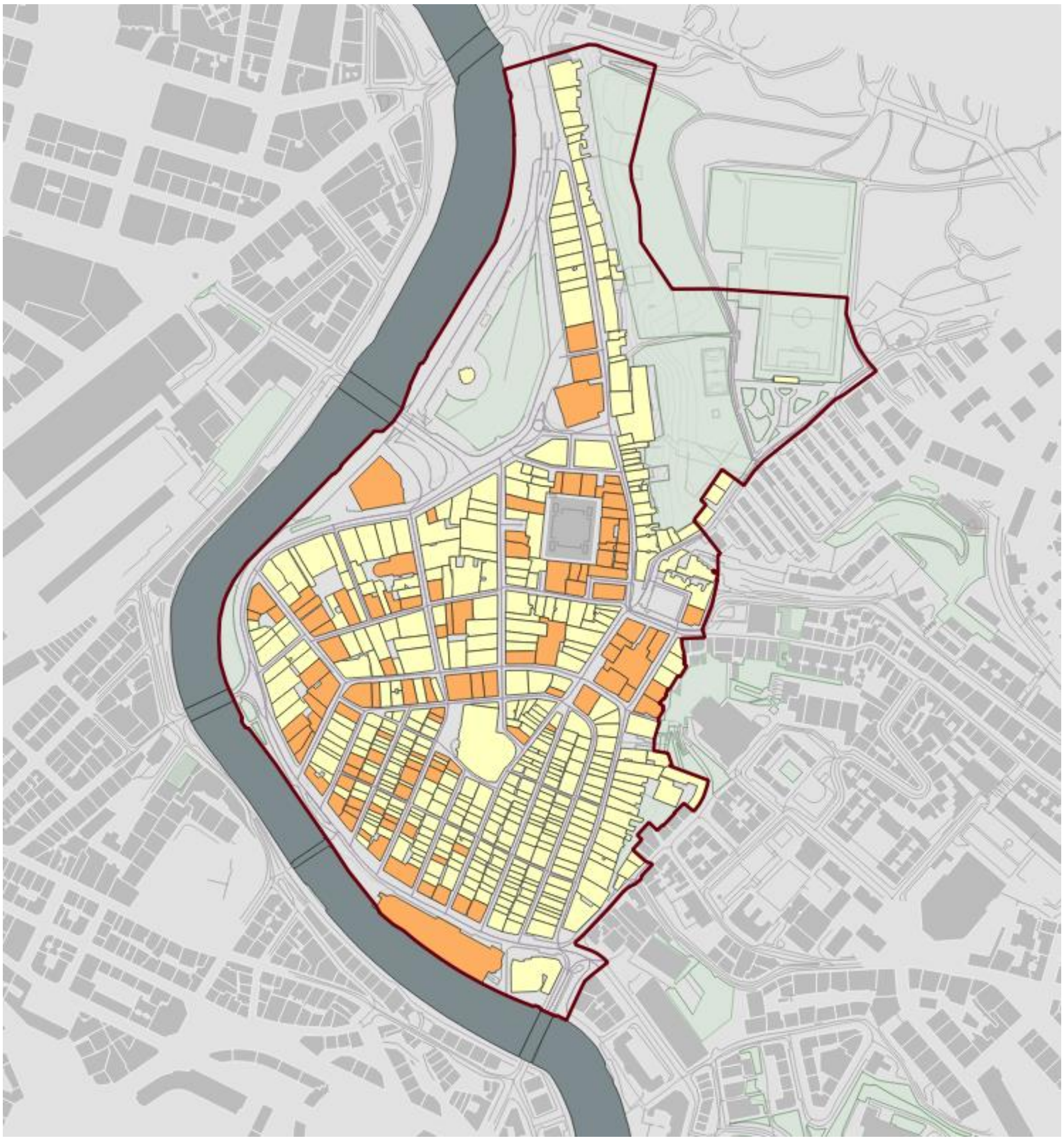


Figure 72. Risk asssessment results for buildings using the index.

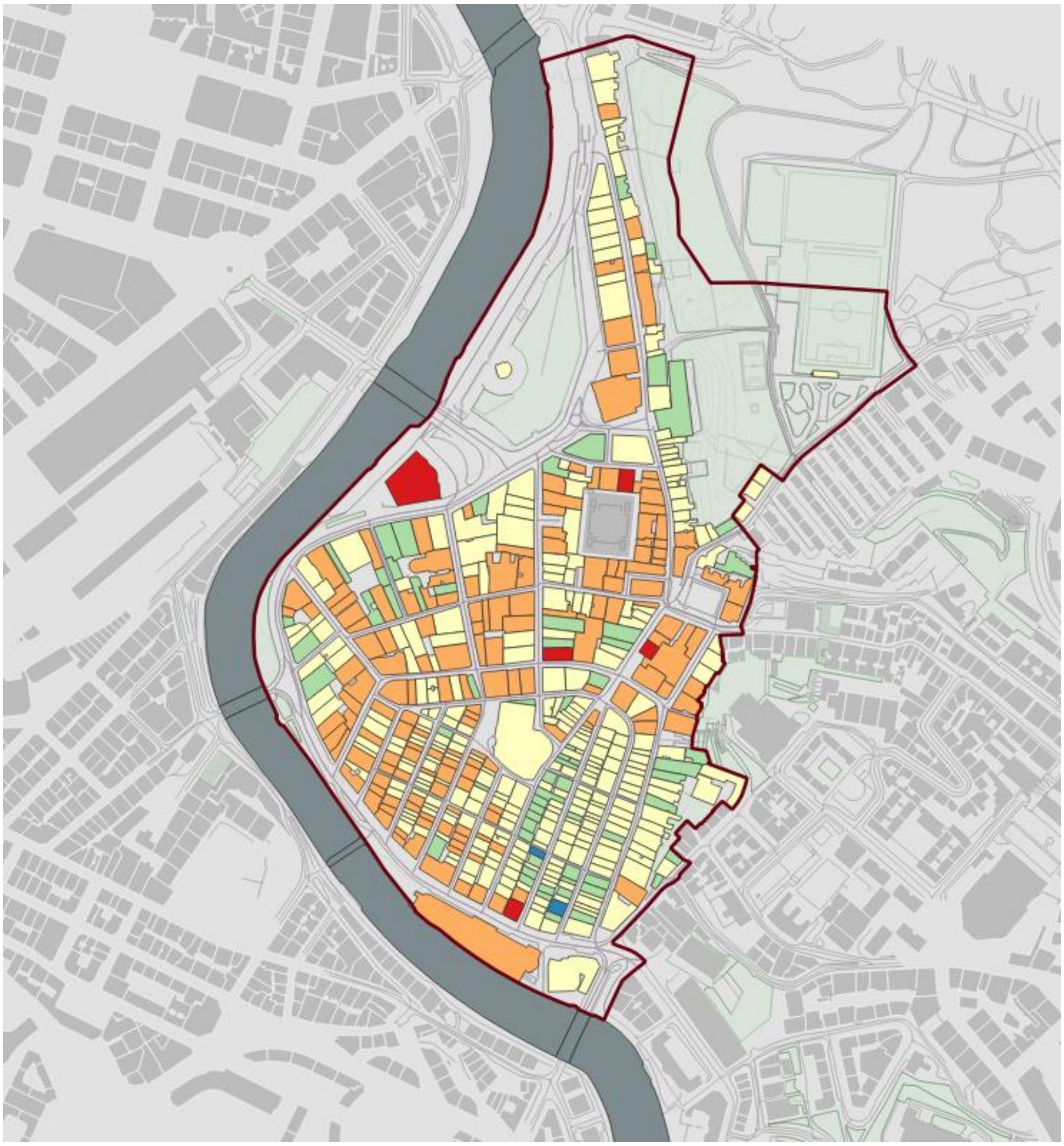
As with the vulnerability, the risk show as a numerical value is shown on Figure 73.



$\mathbf{R_B0} \leq 0.10$	
$0.10 < \mathbf{R_B1} \leq 0.40$	
$0.40 < \mathbf{R_B2} \leq 0.60$	
$0.60 < \mathbf{R_B3} \leq 0.80$	
$0.90 < \mathbf{R_B4} \leq 1.00$	

Figure 73. Risk of buildings for Bilbao using a numerical range.

The minimum value for the risk of building is 0.43 and the highest is 0.69, therefore the representation using this values as minimum and maximum is shown in Figure 74.



$0.43 < \mathbf{R_{B}0} \leq 0.49$	
$0.49 < \mathbf{R_{B}1} \leq 0.54$	
$0.54 < \mathbf{R_{B}2} \leq 0.59$	
$0.59 < \mathbf{R_{B}3} \leq 0.64$	
$0.64 < \mathbf{R_{B}4} \leq 0.69$	

Figure 74. Risk of buildings in Bilbao adjusting the values to minimum and maximum.

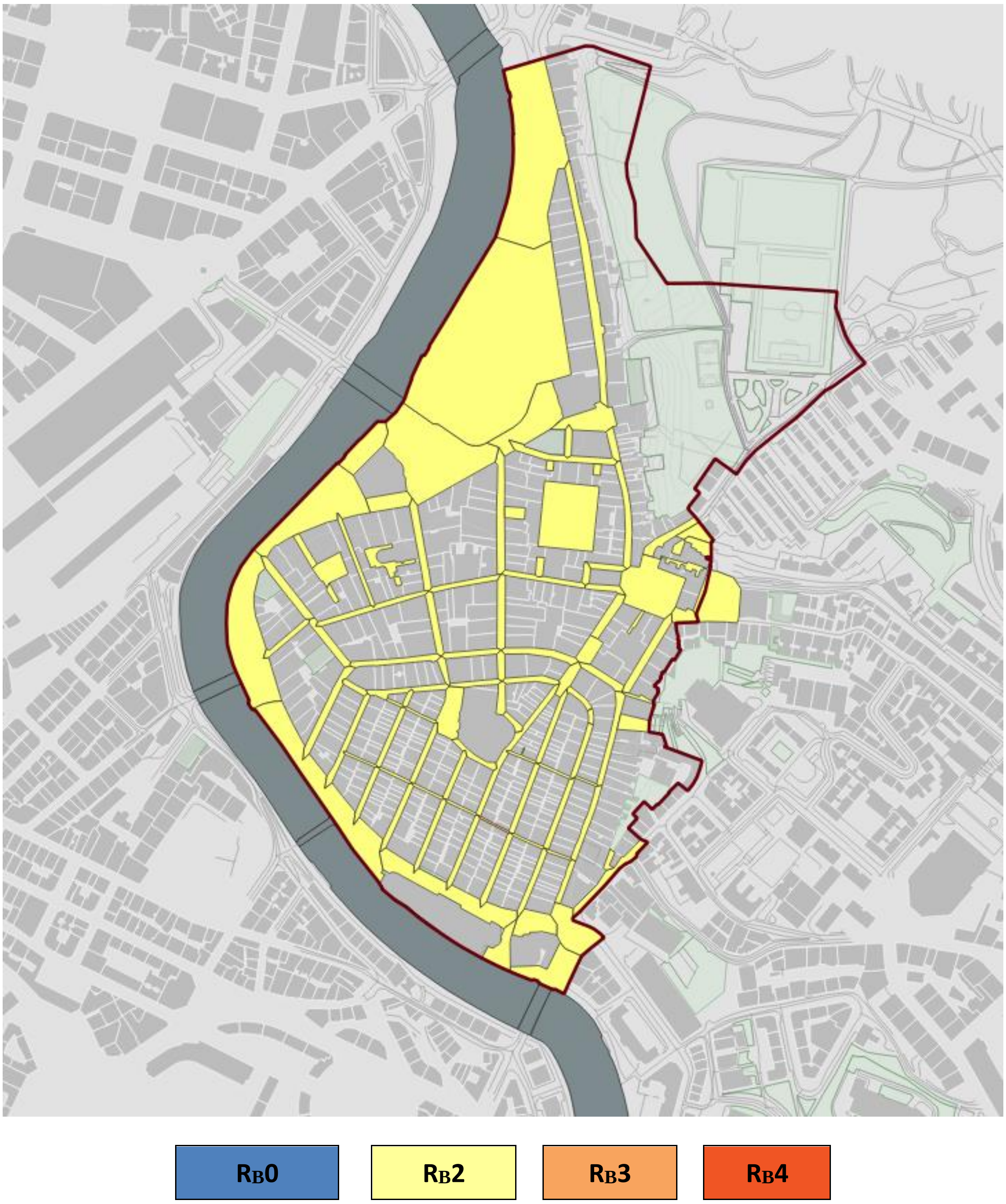
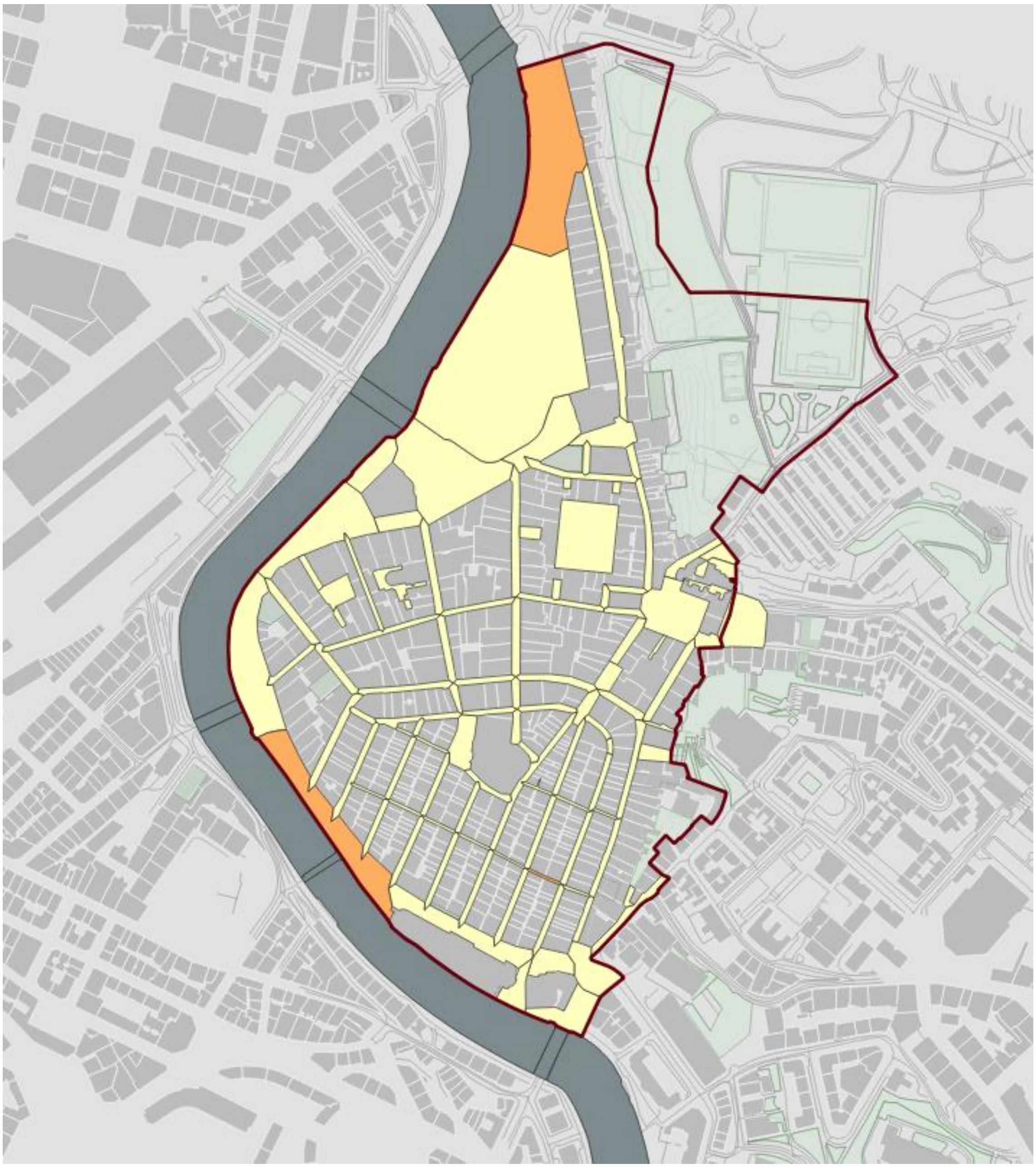


Figure 75. Risk assessment results for public spaces for Bilbao using the index.

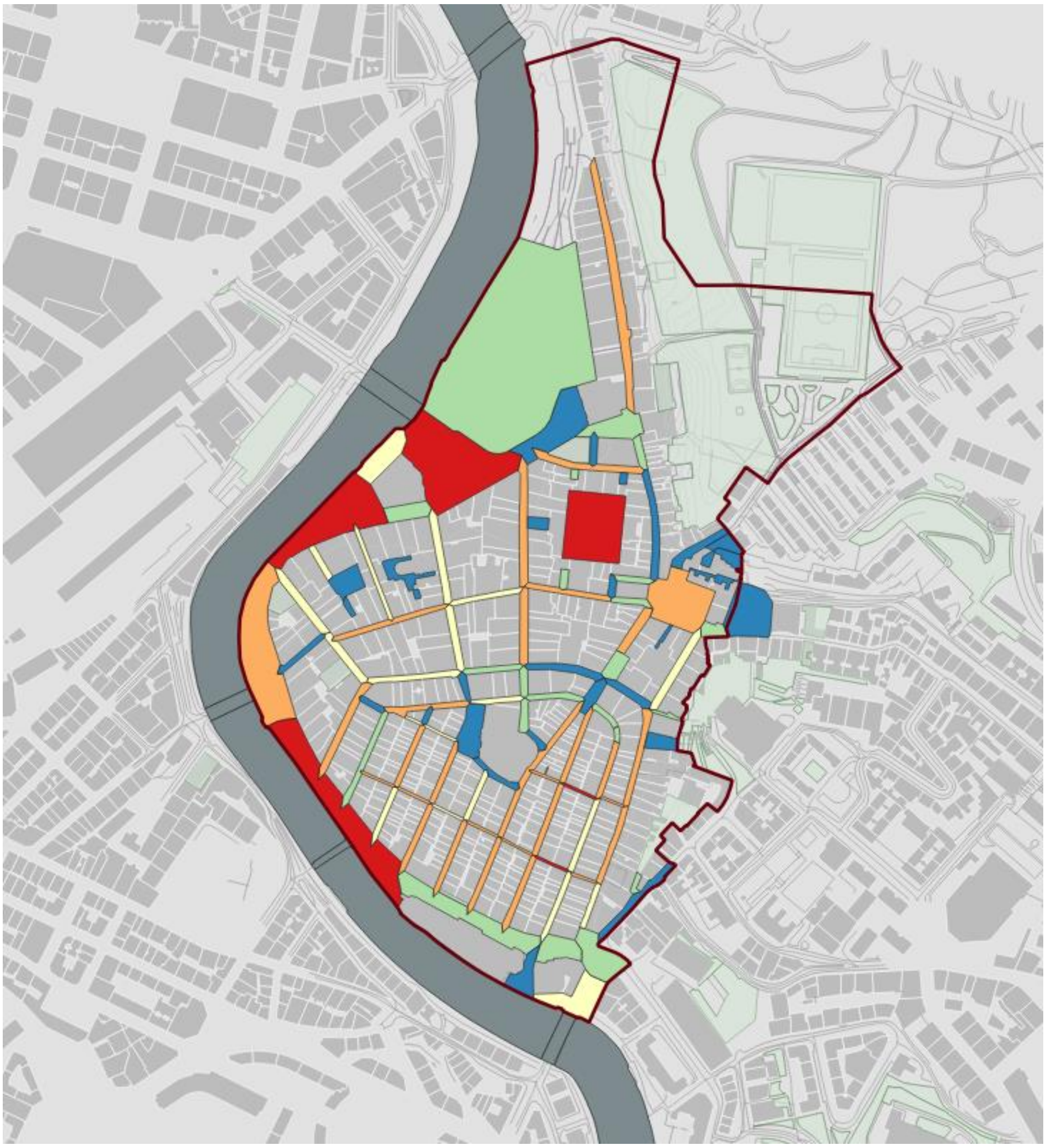
Using the numerical values:



$R_B0 \leq 0.10$	
$0.10 < R_B1 \leq 0.40$	
$0.40 < R_B2 \leq 0.60$	
$0.60 < R_B3 \leq 0.80$	
$0.90 < R_B4 \leq 1.00$	

Figure 76. Risk for public spaces for Bilbao using a numerical range.

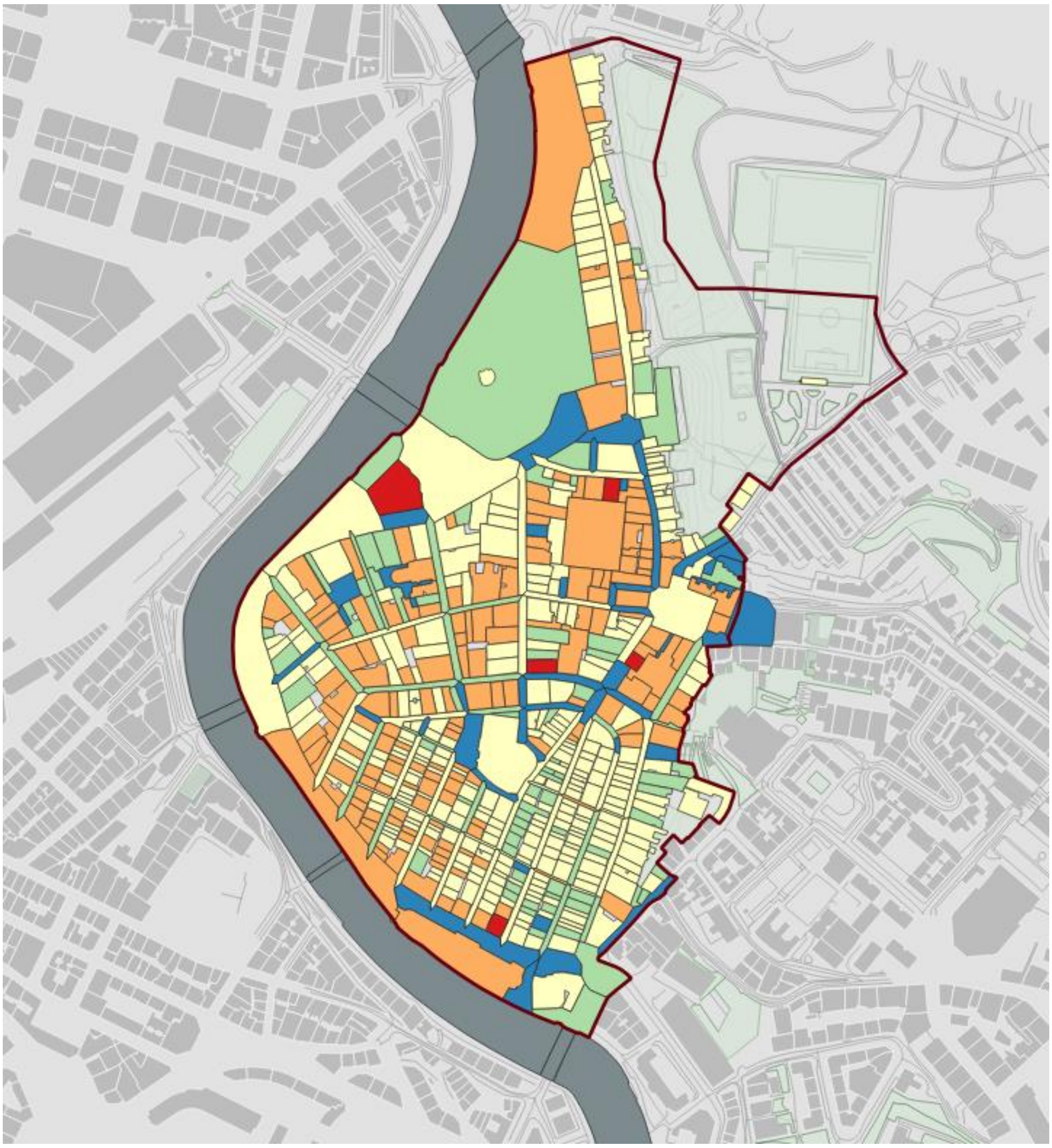
The lowest value in this case for the risk of public spaces is 0,42 and the highest 0,61. The representation using this as minimum and maximum is as follows:



0.42< **RB0** ≤ 0.46	(blue)
0.46 < **RB1** ≤ 0.50	(green)
0.50 < **RB2** ≤ 0.54	(yellow)
0.54 < **RB3** ≤ 0.58	(orange)
0.58 < **RB4** ≤ 0.61	(red)

Figure 77. Risk for public spaces in Bilbao adjusting the values to minimum and maximum.

As a final visualization of results, combination of buildings and public spaces using numerical values and the minimum and maximums to set the ranges:



$0.42 < \mathbf{R_{B}0} \leq 0.49$	
$0.49 < \mathbf{R_{B}1} \leq 0.54$	
$0.54 < \mathbf{R_{B}2} \leq 0.59$	
$0.59 < \mathbf{R_{B}3} \leq 0.64$	
$0.64 < \mathbf{R_{B}4} \leq 0.69$	

Figure 78. Risk for every element in Bilbao adjusting the values to minimum and maximum.

4.6 Discussion of the results

In this chapter the application of the MIVES methodology in the case study of Bilbao, Spain, is shown. The methodology was applied using both the categorization method and the full methodology, to compare the results and test the accuracy of the categorization method.

The categorization method is applied by calculating the vulnerability for a selection of sample elements that provided a statistical repetitiveness of the area, and then extrapolating the results to the ones within the same category. In the case of buildings 9 categories were created while for public spaces there were 10. The results show that, from the 367 categorized buildings, 192 buildings present low V1 vulnerability, 159 medium-low V2, and 16 medium V3 vulnerability. In the case of public spaces, even if the 9 categories provided a very high percentage of representativeness, they all were within the same vulnerability level (V1).

In the case of the application of the full methodology, the results were more varied. When using the vulnerability index, 256 buildings resulted in a low V1 vulnerability, 26 in a medium low V2 vulnerability, 5 in a medium V3 and 6 in a high V4 vulnerability. As for numerical values, 18% of the buildings have a vulnerability value higher than 0.5, with 2 buildings presenting a value higher than 0.6; 1.53% of the buildings presented a low vulnerability of a lower value than 0.3. These percentages varies slightly in the case of risk, but as the hazard value is homogeneous for the area, the results were in the same proportion.

In the case of public spaces, when using the index, 23 resulted in a very low V0 vulnerability, 74 in a low V1, 9 in a medium-low V2 and 1 in a medium V3 vulnerability. When using numerical values, 2.8% presented a vulnerability higher than 0.5, 27.1% being over 0.4. Finally, 19.63% of the public spaces presented a vulnerability lower than 0.2.

4.7 Conclusions

To understand the vulnerability and risk of an area to a hazard and the subsequent impacts provides a realistic approximation to the real context of the historic area, providing support for a more informed and detailed prioritization of interventions and resources. To have a holistic approach of both buildings and urban spaces makes possible to feed a strategy that considers the most vulnerable assets within the area as close as possible to the real situation.

In this chapter the methodology was validated by the modelling of the historic area of Bilbao, comprising 106 public spaces and 522 buildings. The methodology was applied first following the categorization method, by calculating the vulnerability for a selection of sample elements that then were extrapolated to the ones within the same category. It was then followed by the full methodology to check the accuracy of the results obtained by only using a selection of the information that was available.

For the categorization, in the case of the buildings, the 10 resulting categories represented the 70% of the stock, and the vulnerability assessment provided a margin of error of a 2% with respect to the full assessment method. In the case of public spaces, the 9 categories provided a representation of 81.31%, but the margin of error of the results reached 12%, providing less accuracy, as all the categories resulted in an equal vulnerability level. This provided a fast and less data constrained assessment.

As a second step, in the full methodology, the MIVES methodology was applied to all the elements in the area. The semantic information for this model was completed with the real data for each building, obtained from official and open data sources, and completed with fieldwork when necessary. Of the 367 buildings that were categorized, 8 fell into a different vulnerability level using the categorization in comparison with the full methodology, and all of them achieved higher vulnerability levels in the full methodology compared with the categorization. In the case of the public spaces, 87 where categorized, and even if the vulnerability accuracy was very high, all obtained the same level of vulnerability, and the categorization left out the most and less vulnerable elements. Because of this, the results were completed with a numeric calculation of the vulnerability, in contrast to the one provided by the index. This concluded that the homogeneity among the urban spaces in a historic area makes small differences among the indicators which is relevant for the relative comparison of the elements. Thus, the categorization method did not bring so accurate results, and it can be concluded that the use of the vulnerability index in comparison to a numerical result is less accurate in the case of homogeneous areas as it is the case of historic areas.

Hence, the methodology presented its highest potential when applied fully in the case of public spaces, but when applied to the buildings, the categorization method provided very accurate results with less data. In the case of the public spaces, because of the homogeneity of the area, the categorization only included the most similar spaces within the area. This means that the areas with different characteristics where left out of the assessment, and the ones included did not present much differences among them in terms of vulnerability. The categorization method, therefore, will be more reliable when applied to areas with more heterogeneous public spaces.

The risk was then calculated for the area using a very recent and extreme heat wave that took place in July 2022. This requirement applies homogenously to the whole area, as the data is obtained only from one station. If more accurate data is available (for instance data obtained from a denser network of stations within the area or in situ measurements), this requirement could provide more accurate representation of the real situation within the historic area. Alternatively, if different areas are assessed and compared using this methodology, and hazard information from weather stations is available for each area, the hazard indicator would be different for each area under assessment providing accurate representation of their different climatic conditions.

5 Validation of results in an case study (Naples)

5.1 Description of the study case

Naples, or Napoli in Italian, is the most populated city of southern Italy, capital of the Campania region, and of the Metropolitan City of Naples. Within the term of the municipality of Naples live almost a million inhabitants, rising up to more than three million in the metropolitan area. It is located halfway between the volcanic areas Mount Vesuvius and the Phlegrean Fields. It gives its name to the gulf on which shores it sits.

Figure 79. Aerial photo of the historic centre of Naples.

Naples has an enormous historical, artistic, cultural and gastronomic wealth, which led UNESCO to declare its historic centre a World Heritage Site. It births as a polis of Magna

Graecia, And belongs to the Roman city and Byzantine for many centuries. Then it becomes capital of the peninsular Mezzogiorno under the Norman, Swabian, French and Spanish sovereigns. All this history left its mark on Naples. It briefly came under Austrian domination in the early decades of the 18th century, after which it became the political centre of the independent kingdom of Naples and later of the Two Sicilies, ruled by a local branch of the Bourbons. In 1861, it became part of the unified Kingdom of Italy.

In the 20th century, during the fascist period and in the reconstruction after the Second World War, a large part of the outskirts of the city were built. In recent decades, Naples has been endowed with a financial district with skyscrapers, the so-called Centro Direzionale di Napoli (CDN), and infrastructures such as the high-speed train to Rome and Salerno and the metro network. On the other hand, it is also beset by major problems such as organized crime, which is a brake on economic and social development; and the city has suffered major earthquakes so volcanic activity is constantly monitored.

Naples has a transitional climate between the Mediterranean climate (Csa) and the humid subtropical climate (Cfa) according to the Köppen climate classification, because only two summer months have less than 40 millimeters of rain. Due to its proximity to the sea, like most of the cities bathed by the Mediterranean Sea, the climate of Naples is generally mild, although its winter is cool. The average temperature is 8.1 °C in January and 23.7 °C in August. Precipitation is approximately 1,000 mm per year, with the rains concentrating at the beginning of the winter period. However, Naples is one of the sunniest city in Italy.

The city of Naples rises in the plain between the mountain ranges of Campos Flegreos and Vesuvius, at the mouth of the Sebeto river, protected in the north and west by the mountain ranges and by the valleys originated by the channels of its torrents. From the moment of its foundation, the seafaring vocation of the city is very clear and, given its geographical isolation with respect to the inland regions, it is communicated through the sea with other port cities.

The Greeks developped the first settlement within the walled nucleus according to a hypodamic scheme of grid of orthogonal streets. Later, in the Roman age, when the city is part of the empire and the walls are no longer necessary, the city jumps the walls and grows towards the port area. In the Middle Age, the densest areas of growth were incorporated within the new walls that were successively enlarged and the city presented polycentric growth, basically building around public and government buildings or access infrastructures, in contrast to the Linear layout of the classical city. From the year 1000, there is a gradual demographic growth and the urban centre becomes denser, although there is still no clear distinction between the countryside and the city in terms of their structural components and there is economic and social continuity between the city and surrounding area.

From the fourteenth century, once the historic centre was built, the city begins to project towards its territory, developing towards the hills. The royal dynasties succeed one another and the city is progressively embellished with buildings aimed at glorifying the crown, leaving aside the most urgent needs of its inhabitants. Castles and royal palaces were built and their defence systems were perfected, roads are opened for the circulation of the court and numerous royal monuments are erected.

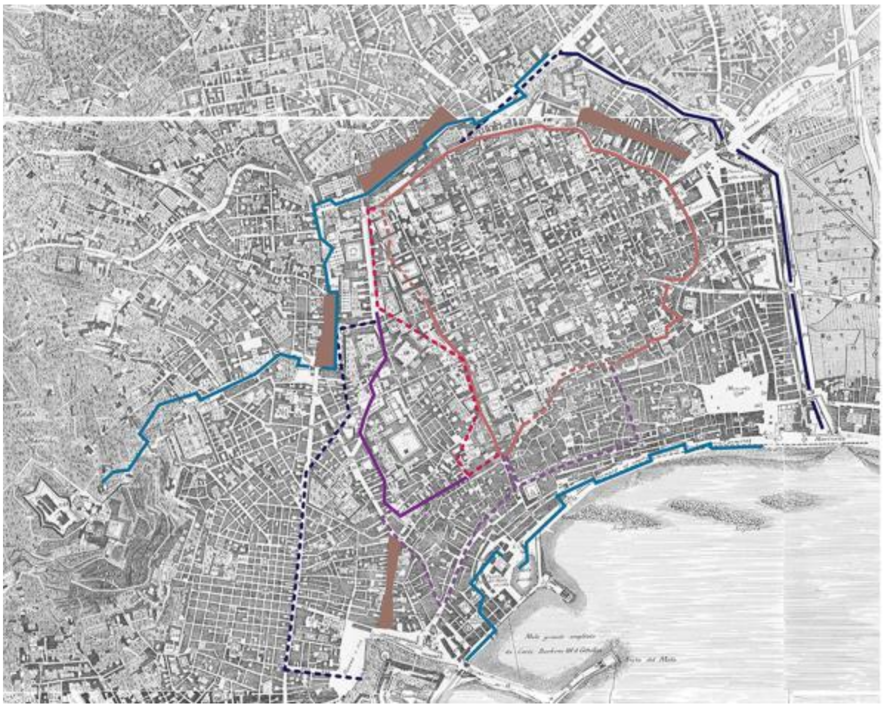


Figure 80. Naples walls development. Wall from fifth century BC (orange line), fourth centrury BC (red), enlargement made by Valentiniano I (lilac), Aragonese wall (dark blue), enlargement by Pedro de Toledo (cyan).

In the fifteenth century, a process of repopulation of the centre with palaces of the nobility takes place due to the growing taste for classical antiquity. The population grows and the city densifies in a disorderly and spontaneous way, although this growth is still absorbed by the intramural area. The buildings go up in height and little by little the green areas begin to be built.

Finally, and due to the pressing need to respond to population growth, during the period of the Spanish reign, Don Pedro de Toledo carried out urban planning measures aimed at solving some of the main problems that afflicted the city. The population increases and all social strata congregates in the city. As a result, there is a population increase from 220,000 inhabitants in the mid-16th century to about 450,000 inhabitants at the beginning of the 17th century. Precarious housing becomes part of the urban landscape.

Against this background, and in view of the disorderly growth of the city, the government decides to veto the construction of new homes, first in the area near the wall and then in the suburbs. This process will produce spontaneous and disorganized growth, basically promoted by private initiative, but which will present morphological and functional continuity with the intramural city. The city will exceed the limit of the walls by growing in the suburbs through the same mechanisms of the interior part.

Figure 81. The building stain in the mid-16th century (left) and the building development in the mid-17th century (right).

This dynamic of growth of the city will change in the eighteenth century with the suppression of the real pragmatics. Thus, a lack of unity appears in the urban fabric and the eighteenth-century image of the city is that of a fragile unity made up of fragments. Urban expansion is more fragmented and heterogeneous than in the 17th century.

Although there were several attempts to solve the main urban problems that plagued the city, things did not improve and, when at the end of the 19th century the city is hit by a cholera epidemic, a vast disembowelling operation begins in a large part of the centre of the city, called *Risaneamento*.

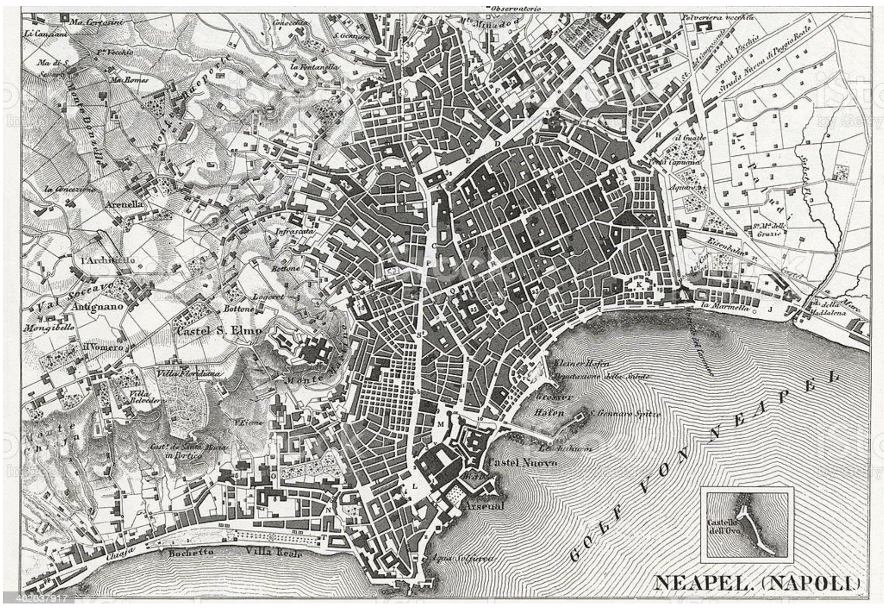


Figure 82. Engraved illustrations of the City of Naples from Iconographic Encyclopedia of Science, Literature and Art, in 1851.

From then on, the dynamics changes and the city begins to grow through large expansion and urban rehabilitation interventions, acquiring a metropolitan character. The great operation of *Risaneamento*, of an undoubtedly speculative nature, will open part of the medieval fabric, especially in the neighbourhoods located in the southeastern part of the ancient city. In 1904, a law is passed to activate the regional economy with the definition of two industrial areas: one in the far east, already existing for at least a century, and another new one to the west, outside the city, near the island of Nisidia, which will constrain the growth of the city both to the west and to the east.

5.1.1 Area of study

The selected area for the case study is the oldest part of the city, the historic area that was originally constrained by the Greek and roman city walls. This area is characterized by very narrow streets delimited by high buildings that are the product of centuries of stratification and organic growth. It is a very dense area, with four main categories of building morphology: narrow buildings, buildings articulated around a courtyard, singular buildings and buildings with a complex layout.

Figure 83. Area selected for the case study of Naples.

The whole centre of Naples is a Unesco World Heritage Site. Therefore, there are several protection and listing legislations that regulate the area. The General Urban Planning Plan of 1972 (Ministerial Decree No. 1829, March 31, 1972) identifies the protected area of the historic centre, where all interventions must be approved by the corresponding

Soprintendenza. The provisions of Law No. 47 of February 28, 1985 on "Rules on Urban Planning and Control of Buildings, Sanctions, Recovery and Redevelopment of Abusive Works" are applicable to the area, and establishes the specifications of height and spacing of the buildings. A large number of buildings in the city are designated under the terms of Law no. 1089 of June 1, 1939, central piece of Italian legislation related to the protection of heritage that was later merged into the code of cultural heritage and landscape of D. Laws n.42/2004.

This code of 2004 feeds the “Variant to the general regulatory plan of the historical centre”, approved in 2004, which catalogues and sets the regulations for the intervention and restoration of the buildings within the area. This plan is the one used for the gathering of semantic information in this study. As the historic area is very complex, and a lot of stratification of different periods is common among the buildings, the code catalogues all the buildings stating the main morphology, representative constructive period and characteristics, creating 125 categories. The study area is composed of 17 of these categories. These categories where used to feed the semantic information of the model, namely, the alternatives for these indicators: year of construction, sensitivity of the materials and protection level. The 17 categories have these main characteristics:

- Nº 64. Pre-nineteenth-century basic building unit with courtyard. Pre-nineteenth-century building unit typified by an structure articulated around an open space and by the sequence of door, entrance hall, staircase, courtyard and, generally, garden. Characterized by wide stone walls on the façade, traditional mortars and timber carpentry elements. Provided with a high protection that limits most interventions.
- Nº69. Pre-nineteenth-century building unit or block. Pre-nineteenth-century basic building unit; building with compact structure, a direct door-staircase sequence, with or without entrance hall, and absence of open spaces inside the building volume. Characterized by wide stone walls on the façade, traditional mortars and timber carpentry elements. Provided with a high protection that limits most interventions
- Nº73. Pre-nineteenth-century basic self-contained building unit. Pre-nineteenth-century basic building unit characterized by an isolated building in a relevant lot, which does not have repetitive characteristics such as to configure the urban fabric and which consequently represents a building example in its own right. Distinguished by wide stone walls on the façade, traditional mortars and timber carpentry elements. Provided with a high protection that limits most interventions
- Nº76. Nineteenth-century basic building unit with courtyard. Nineteenth-century building unit characterized by a structure articulated around an open space and by the sequence of door, entrance hall, staircase, courtyard and, generally, garden. Typified by wide stone walls on the façade, traditional mortars and timber carpentry elements. Provided with a high protection that limits most interventions.
- Nº79. Nineteenth-century building unit or block. Nineteenth-century basic building unit composed of buildings with compact structure, a direct door-staircase sequence, with or without entrance hall, and absence of open spaces

inside the building volume. Characterized by wide stone walls on the façade, traditional mortars and timber carpentry elements. Provided with a high protection that limits most interventions.

- Nº86. Late nineteenth early twentieth-century building unit with courtyard. Late nineteenth-early -twentieth century building unit, structure articulated around an open space and by the sequence of door, entrance hall, staircase, and courtyard and, generally, garden. Resulting from restructuring processes of pre-existing buildings that took place in the late nineteenth early twentieth century, with modification of the original model in functional, structural and compositional ways. Characterized by stone or brick walls on the façade, traditional mortars and some painted timber carpentry elements. Provided with a medium or typological protection that limits some interventions.
- Nº92. Late nineteenth early twentieth-century building unit or block. Late nineteenth early twentieth-century building unit built in lots generally preordained by overall urban projects and characterized by a direct hall-staircase sequence and by the absence of open spaces inside the building volume. Resulting from restructuring processes of pre-existing buildings that took place in the late nineteenth early twentieth century, with modification of the original model in functional, structural and compositional ways. Characterized by stone or brick walls on the façade, traditional mortars and some painted timber carpentry elements. Provided with a medium or typological protection that limits some interventions.
- Nº102. Pre-nineteenth-century special building units with a unitary structure. Pre-nineteenth-century special building unit characterized by the presence of a unitary compartment, by the centrality of its constituent space and by the single or predominant access system. It includes mostly the churches in the context of larger monumental complexes. Distinguished by wide stone walls on the façade, traditional mortars, painted glass elements and timber carpentry and decorative elements. Provided with a very high monument protection that limits and regulates interventions.
- Nº103. Pre-nineteenth-century special modular structure building unit. Pre-nineteenth-century special building unit characterized by a structure with rooms repeated in sequence, of similar size, and by linear distribution systems such as corridors, arcades, balconies etc. This category mostly includes monasteries, hospitals, administrative offices, military buildings and any other monumental building of a serial type aggregated over time mainly in conventual insulae, for welfare, educational and hospitality purposes in general. Characterized by wide stone walls on the façade, traditional mortars, painted glass elements and timber carpentry and decorative elements. Provided with a very high monument protection that limits and regulates interventions.
- Nº104. Pre-nineteenth-century special building unit with a complex modular structure. Building unit characterized by a structure in which the presence of rooms repeated in sequence, of similar size, is combined with the consistent

presence of rooms of other nature and size, originally built for the performance of complementary functions. The pre-nineteenth-century special units attributable to the aforementioned characteristics include monastic, hospital, military and any other monumental context in the entirety of the main buildings and the plurality of serial-type buildings aggregated over time, mostly in the conventual insulae, for welfare, educational and hospitality purposes in general. Characterized by wide stone walls on the façade, traditional mortars, painted glass elements and timber carpentry and decorative elements. Provided with a very high monument protection that limits and regulates interventions.

- N°105. Pre-nineteenth-century special building unit with a singular or non-repeated system. Special building unit which, given its structural, distributive and compositional characteristics, is not attributable to any codified building type (single system) or repeatedly found in the building fabric. This category includes castles, royal palaces, walls, noble buildings that have incorporated squares or urban open spaces within them, and any other monumental unit that for the individuality of the structural and compositional distributive characteristics, or even only the dimensional ones, of the building sample qualify in the urban fabric as exceptions. Characterized by wide stone walls on the façade, traditional mortars, painted glass elements and timber carpentry and decorative elements. Provided with a very high monument protection that limits and regulates interventions.
- N°107. Nineteenth-century special modular structure building unit. Special building unit characterized by a structure with rooms repeated in sequence, of similar size, and by linear distribution systems such as corridors, arcades, balconies etc. The buildings attributable to the aforementioned characteristics include convents, hospitals, office buildings and administrative offices in general, military buildings, prisons, schools, markets, and any other monumental building that, in the typical nineteenth-century process of functional specialization of civil construction, has been carried out according to modular schemes. Characterized by stone or brick walls on the façade, traditional mortars and some painted timber carpentry elements. Provided with a very high monument protection that limits and regulates interventions.
- N°109. Nineteenth-century special building unit with a singular or non-repeated system. This includes the galleries, the exedras delimiting the large urban squares, and any other monumental unit that for the individuality of the structural and compositional distributive characteristics, or even only the dimensional ones, of the building sample qualify within the urban fabric as exceptions. Characterized by stone or brick walls on the façade, traditional mortars and some painted timber carpentry elements. Provided with a very high monument protection that limits and regulates interventions.
- N°111. Late nineteenth early twentieth-century modular structure building unit. Building unit characterized by a structure with rooms repeated in sequence of similar size and by linear distribution systems such as corridors, arcades, balconies, etc. This category commonly includes hospitals, office buildings and

administrative offices in general, military buildings, prisons, schools, markets, hotels, factories and any other building which, in the process of expansion and industrialization of the early twentieth century, has been carried out according to modular schemes. Characterized by stone or brick walls on the façade, traditional mortars and more modern carpentry elements. Provided with a medium or typological protection that limits some interventions.

- Nº112. Late nineteenth early twentieth-century special building unit with a complex modular structure. Building unit characterized by a structure in which the presence of rooms repeated in sequence, of similar size, is combined with the consistent presence of rooms of other nature and size, originally built for the performance of complementary functions. The buildings attributable to the aforementioned characteristics include hospital, military, executive, production modular structures and any other similar context composed of main buildings and unitarily designed serial spaces. Characterized by stone or brick walls on the façade, traditional mortars and more modern carpentry elements. Provided with a medium or typological protection that limits some interventions.
- Nº113. Late nineteenth early twentieth-century special building unit with a singular or non-repeated system. These include monumental and non-monumental units that for the individuality of the structural and compositional distributive characteristics, or even only the dimensional ones, of the building sample qualify in the urban fabric as exceptions. Characterized by stone or brick walls on the façade, traditional mortars and more modern carpentry elements. Provided with a medium or typological protection that limits some interventions.
- Nº 124. Newly formed building unit. Buildings both residential and intended for other uses, built after the Second World War on free or demolition sites. Characterized by brick walls on the façade and more modern carpentry and decorative elements. Provided with a basic protection that allows most interventions.

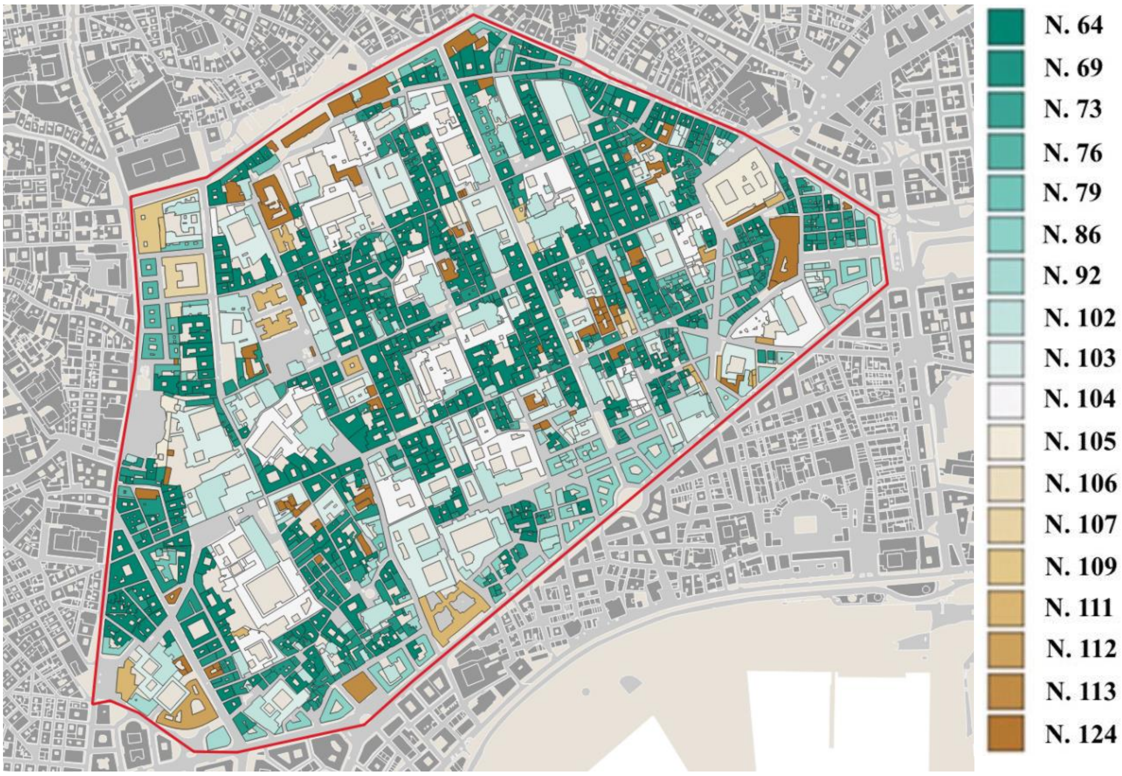


Figure 84. Distribution of construction categories in the historic area of Naples.

5.2 The model and data base

As for Bilbao, the methodology was tested in Naples through a GIS model. The model was generated through two main steps. First, the generation of the geometry, creating mainly the buildings and the open spaces as polygons. Secondly, the insertion of the semantic information of the polygons regarding the indicators data for each of the elements.

In the case of Naples a base polygon layer for the buildings was available through the open data base of the *Comuna di Napoli*, or Naples municipality. On the contrary, there was no available polygon layer for the public space. In the case of Bilbao, it was possible to develop this layer manually, but because of the complexity of the Naples historic area, this was not a possibility for this case study. Therefore, the results for the public spaces in the case of Naples needed to be visualized and provided through the use of raster images. Hence, the semantic information to feed the indicators, and consequentially the final vulnerability and risk assessment will be provided in the same way, through pixel values and visualised as an image, in contrast with the element-based representation through polygons used in the Bilbao case.

Several sources were used to feed the geometry of the model. As mentioned, the basic building 2D geometry was collected from the open database of the *Comuna di Napoli*. For the 3D information on both the terrain and the geometry of the buildings, the same method used in Bilbao was applied, by means of the combination of the data gathered from Naples database and the cadastre, Lidar and the Digital Terrain Model (DTM). LiDAR provided the DSM of the area of interest. By using the LIDAR and DTM data, the height of the buildings and their altitudes was obtained.

This model was completed with semantic information collected from public data sources and processed. As for the previous case study, data related to physical and environmental properties such as SVF, NDVI, solar radiation, etc. was obtained from either satellite data (Copernicus and Landsat) or the processing of the satellite data through the Urban Multi-scale Environmental Predictor (UMEP) for QGIS (Lindberg et al. 2018).

The data feeding the historical typologies and protection status of the buildings was collected from the Implementation Rules Coordinated Text Of The Variant To The Master Plan For The Historic Center, Eastern Area, North-Western Area (*Norme d'attuazione testo coordinato. Variante al piano regolatore generale centro storico, zona orientale, zona nord-occidentale*) approbed by the G*iunta regionale della Campania* in 2004, regulating the protection of Naples historic area. These regulations provide typological classification of the buildings taking into consideration their date of construction, constructive characteristics as well as morphological and cultural value. These were, therefore, the categories used to feed the indicators for date of construction related to thermal comfort, sensitivity of the materials and protection value for the buildings.

The complexity of this case study and the limited available data tested the replicability of the methodology. As it has been explained, it was not possible to obtain separate polygons for the public spaces, and the results are visualized via raster images. This fact made not possible to implement the categorization method proposed in chapter 3 and implemented in Bilbao, as it is necessary to divide the geometry into separate elements to feed that process.

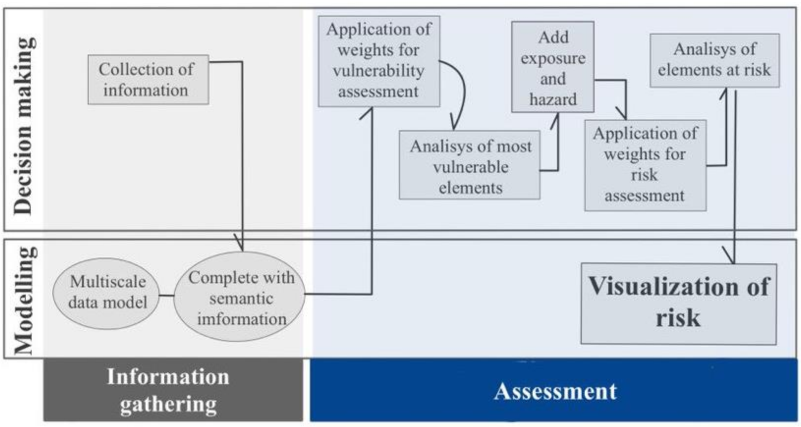


Figure 85. Workflow process for the risk assessment in the case of Naples.

Because of this, and to provide an example of the application of the methodology in a more complex case study, the MIVES method will be used to provide the vulnerability and risk assessment of the whole area, following the process presented in Figure 85.

5.3 Vulnerability assessment

In this section, the vulnerability assessment using MIVES methodology is carried out. In this case, all of the elements were assessed individually in the case of the buildings, and a raster image of public space vulnerability was developed. As previously mentioned, in the case of Naples, because of the limitations in data availability, some indicators could not be used, namely: acoustic pollution, state of conservation, the link to historical events and the presence of the elevator in the case of buildings (Table 76), and relevance, air pollution, accessibility and the link to historical events in the case to public spaces (Table 75). For the replicability of the methodology, it has been applied not taking into consideration those indicators, and maintaining the proportion of the weights that were calculated in chapter 3. The method for this is explained in section 3.2.3.

Req	Criteria		Indicators				
Sensitivity	0.54	Physical	0.35	Albedo	**Albedo of the space**		VALUES
					High	> 0.6	0.00
					Medium	0.25 < x < 0.6	0.70
					Low	<0.25	1.00
			0.33	NDVI	**Normalized Difference Vegetation Index**		VALUES
					Low	X < 0.2	0.00
					Medium	0.2 < x < 0.5	0.35
					High	0.5 < x	1.00
			0.32	SVF	**Sky view Factor**		VALUES
					Very high	> 0.65	0.00
					High	0.5 to 0.65	0.20
					Medium	0.35 to 0.5	0.80
					Low	< 0.35	1.00
	0.46	Environmental	1.00	Solar radiation	**Shadow fraction**		VALUES
					Very low	<0.2	0.00
					Low	0.2-0.4	0.20
					Medium	0.4-0.7	0.80
					High	0.7-1	1.00

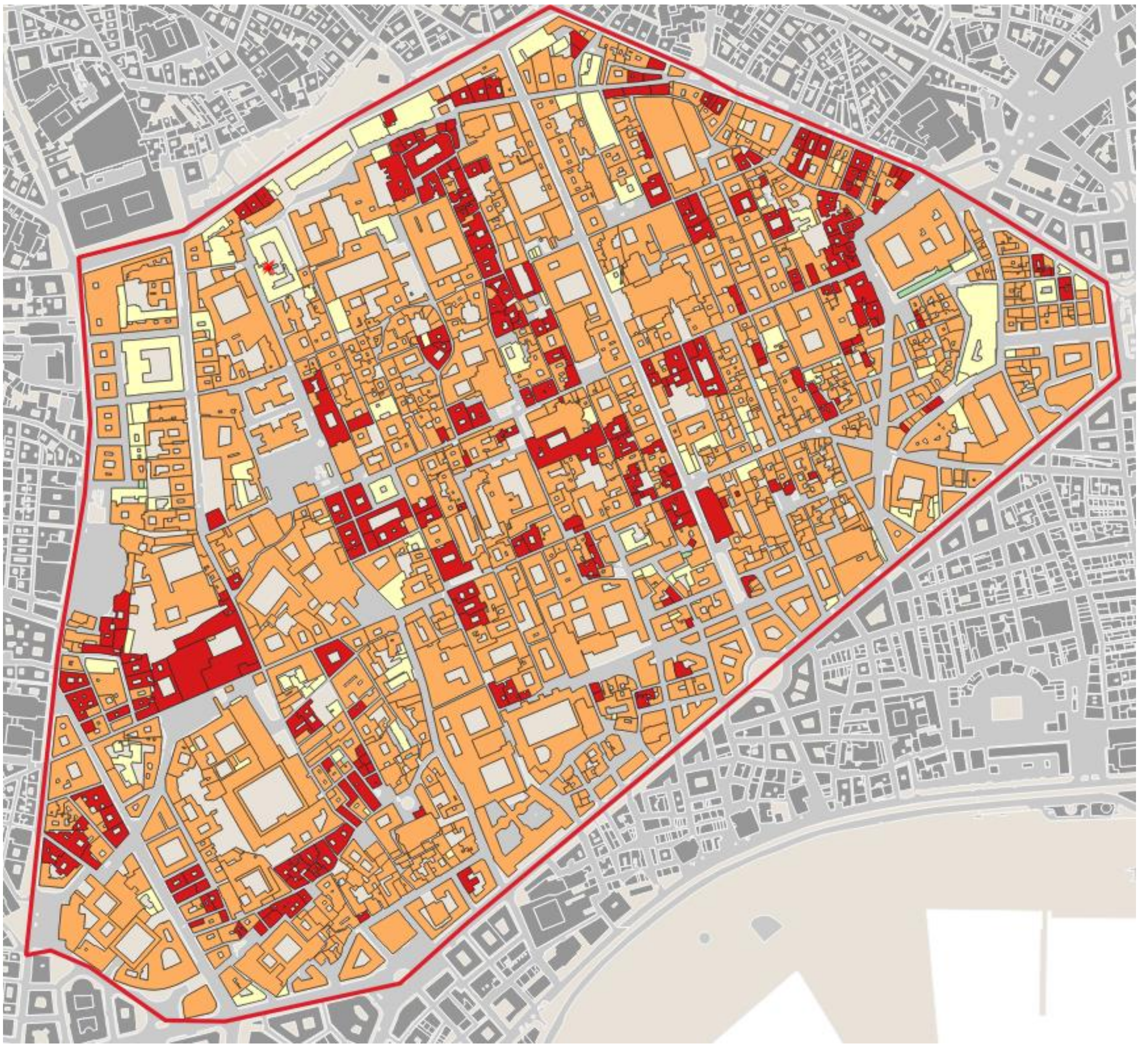
Table 75. Decision tree for the public spaces in the case study of Naples.

As the indicators of coping capacity of the public space are not available in this case, the sensitivity is equal to vulnerability.

Req	Weight	Criteria	Weight	Indicators	Class	Range	VALUES
Sensitivity	0.28	Environmental	1.00	Solar radiation (Shadow fraction)	Very low	<0.2	0.00
					Low	0.2-0.4	0.20
					Medium	0.4-0.7	0.60
					High	0.7-1	1.00
	0.36	Social sensitivity	0.25	Population density (Inhabitants per sqm of residential area in the building)	Empty	0	0.00
					Low	X<0.02 habs/m^2	0.26
					Medium	0.02 < x < 0.05 habs/m2	0.61
					High	0.05 < x habs/m2	1.00
			0.30	Date of construction (thermal comfort) (Date of construction)	>1970		0.00
					1943<x<1970		0.40
					1870<x<1943		0.69
					1800<x<1870		0.56
					<XVIII century		1.00
			0.45	% of vulnerable population (Population older than 65 years of age)	Low	X < 25%	0.00
					Medium	25% < x < 40%	0.62
					High	40% < x	1.00
	0.21	Physical	1.00	Date of construction (linked to vulnerability of materials) (Date of construction)	>1970		0.00
					1943<x<1970		0.40
					1870<x<1943		0.69
					1800<x<1870		0.56
					<XVIII century		1.00
	0.15	Economic	1.00	Primary use (Primary use)	Residential		0.82
					Industrial		0.48
					Public use (social/cultural)		0.84
					Touristic		0.43
CC	1.00	Cultural value	1.00	Level of protection (Protection level of the building)	None	None	0.00
					Low	Basic / ambient	0.28
					Medium	Typological	0.59
					High	Integral	0.81
					Very high	Monument	1.00

Table 76. Decision tree for the buildings in the case study of Naples.

The values and weights calculated in the previous chapter are applied to the semantic information gathered in the model, providing as a result the vulnerability. The results for both buildings and public spaces are shown from Figure 86 to Figure 90.



$\mathbf{S_N 0} \leq 0.10$	
$0.10 < \mathbf{S_N 1} \leq 0.40$	
$0.40 < \mathbf{S_N 2} \leq 0.60$	
$0.60 < \mathbf{S_N 3} \leq 0.80$	
$0.90 < \mathbf{S_N 4} \leq 1.00$	

Figure 86. Sensitivity of buildings in the Naples case sudy.

$\mathbf{CC_N0} \le 0.33$	
$0.33 < \mathbf{CC_N1} \le 0.75$	
$0.75 < \mathbf{CC_N2} \le 1.00$	

Figure 87. Coping capacity of buildings in the case study of Naples.

As shown on Table 77 vulnerability has different levels according to the sensitivity and coping capacity of the element, from V0 to V5.

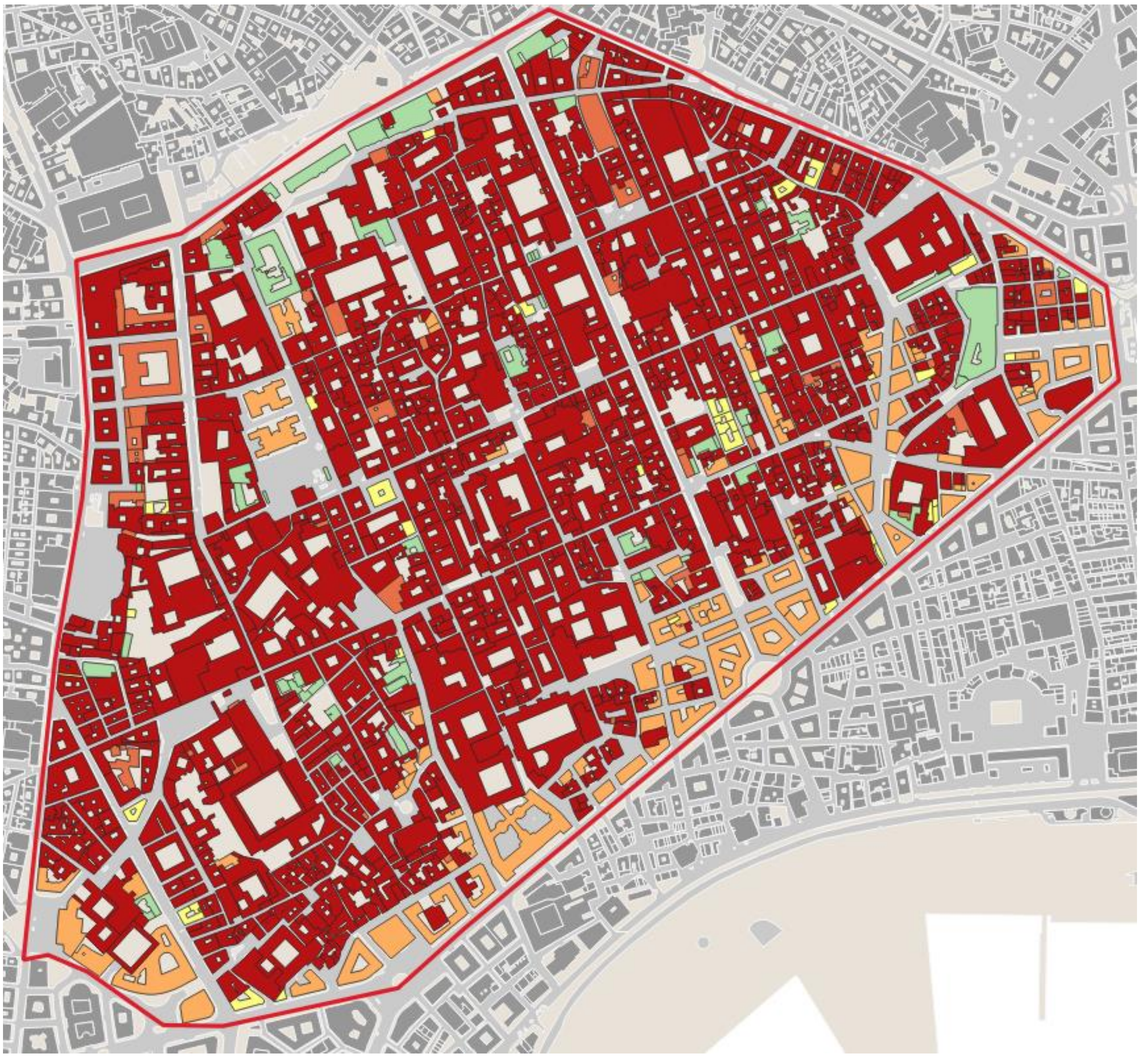
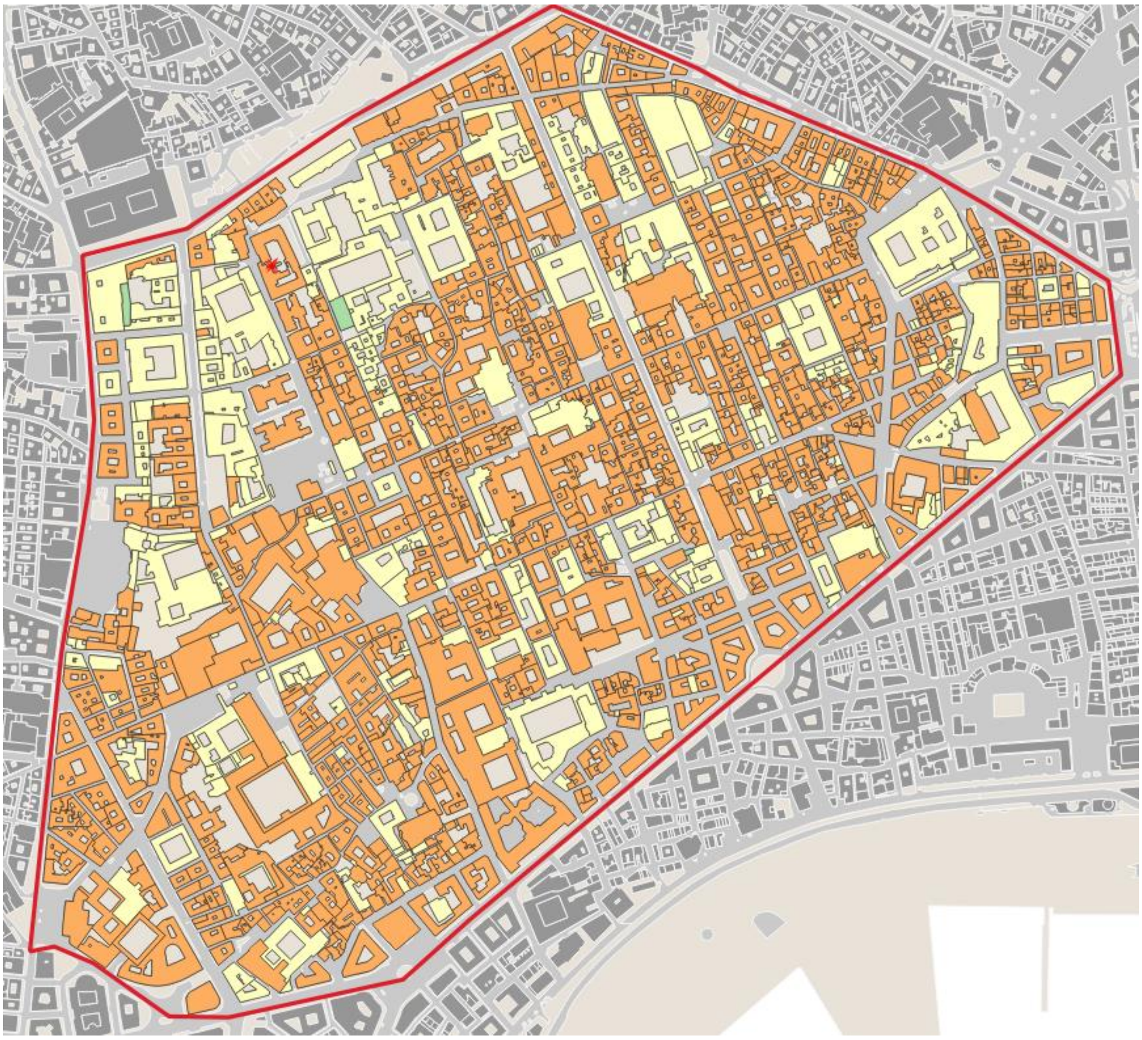


Figure 88. Vulnerability of the buildings for the case study of Naples using the index.

		Sensitivity: low to high				
		S0	S1	S2	S3	S4
Lack of coping capacity: low to high	CC1	V_N0	V_N1	V_N1	V_N2	V_N3
	CC2	V_N1	V_N2	V_N2	V_N3	V_N4
	CC3	V_N2	V_N3	V_N4	V_N5	V_N5

Table 77. Vulnerability levels and colour legend.

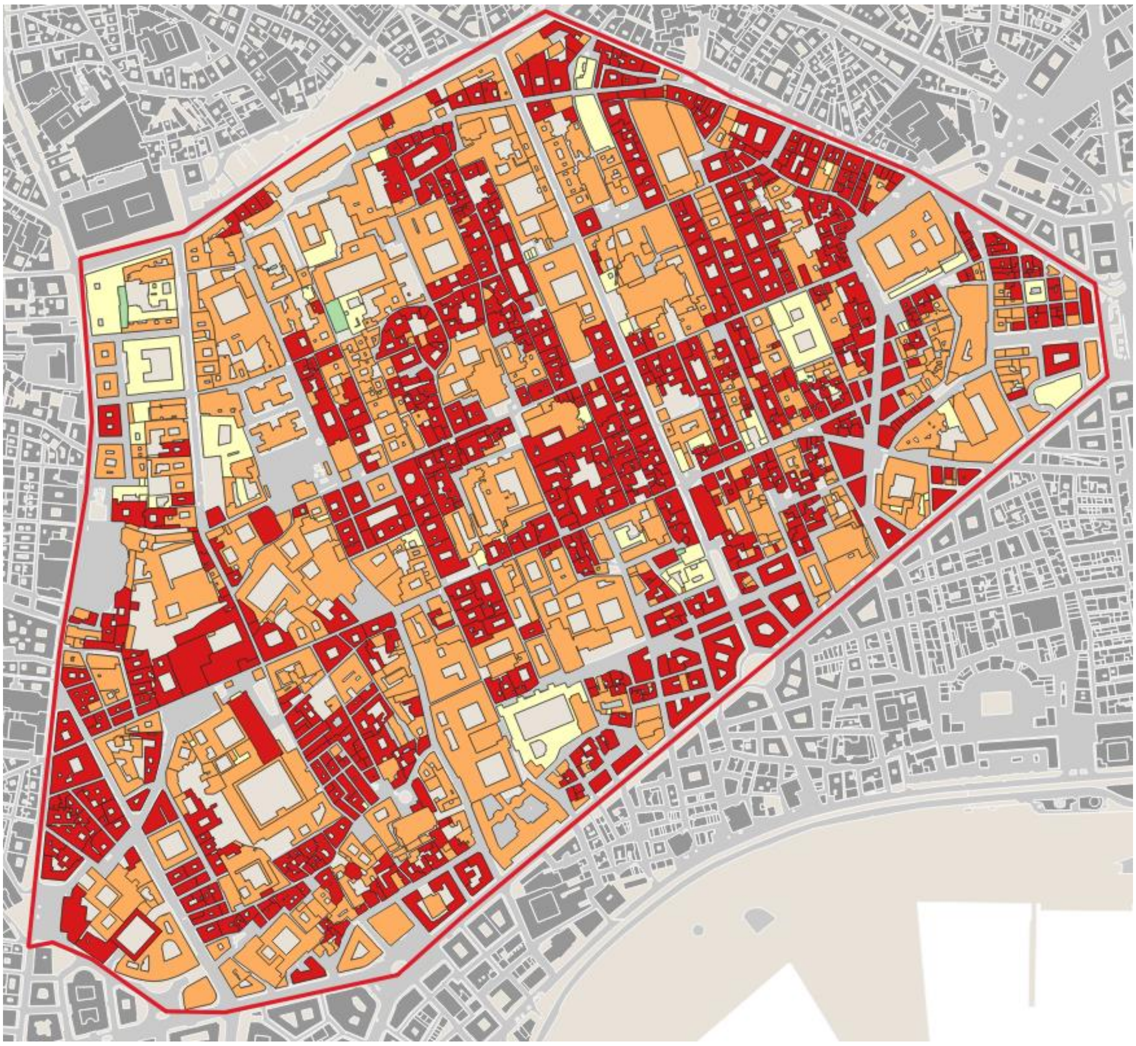
Using the numerical values the visualization changes to this:



$\mathbf{V_N0} \leq 0.10$	
$0.10 < \mathbf{V_N1} \leq 0.40$	
$0.40 < \mathbf{V_N2} \leq 0.60$	
$0.60 < \mathbf{V_N3} \leq 0.80$	
$0.90 < \mathbf{V_N4} \leq 1.00$	

Figure 89. Vulnerability for buildings in Naples using a numerical range.

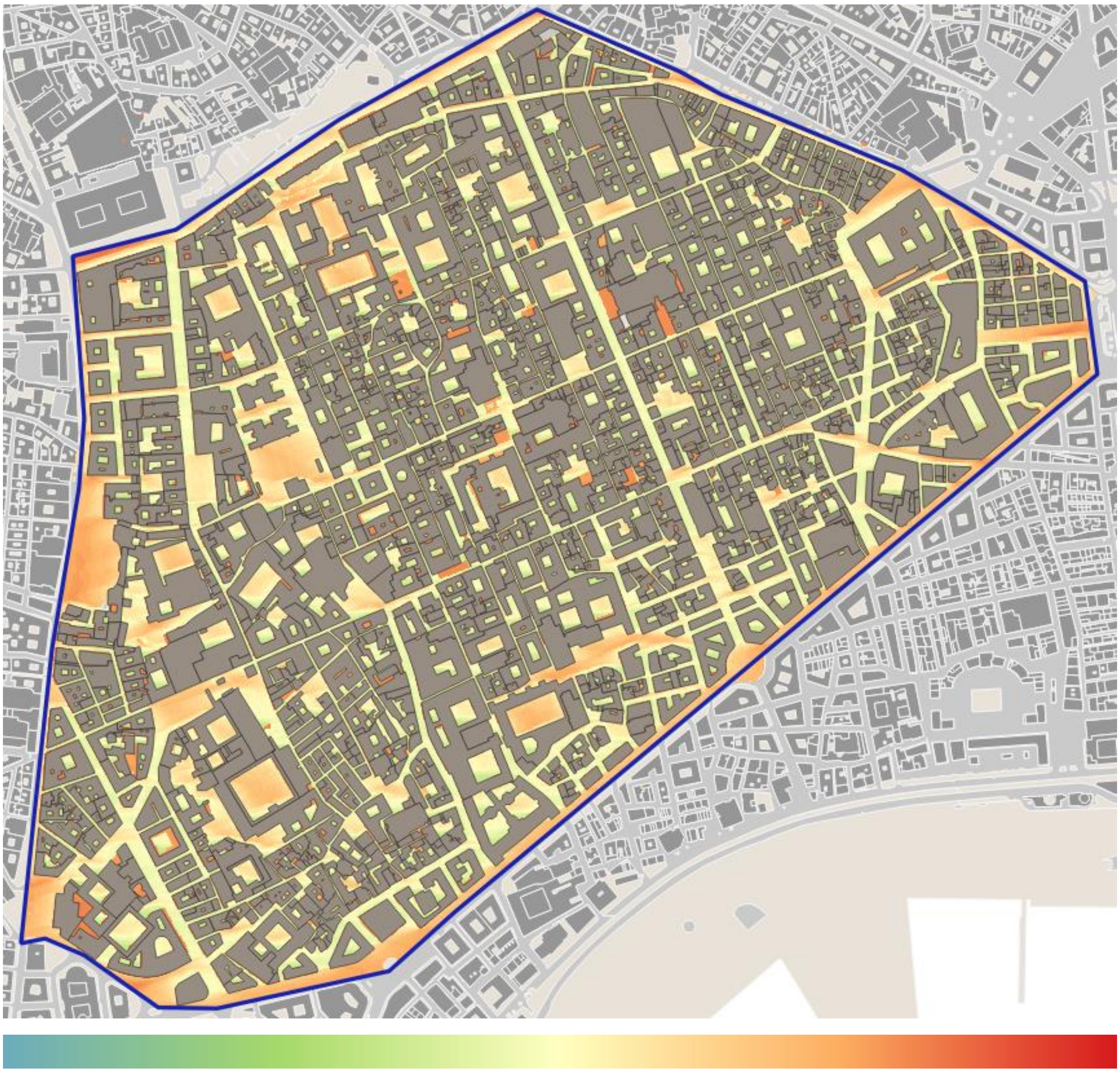
The values for the vulnerability of buildings present a minimum of 0.13 to a maximum of 0.77. For a more accurate representation of results, the visualization is modified readjusting the range using this values as minimum and maximum and dividing the in between values equally as shown on Figure 90.



$0.13 < \mathbf{V_N0} \leq 0.26$	
$0.26 < \mathbf{V_N1} \leq 0.39$	
$0.39 < \mathbf{V_N2} \leq 0.52$	
$0.52 < \mathbf{V_N3} \leq 0.65$	
$0.65 < \mathbf{V_N4} \leq 0.77$	

Figure 90. Vulnerability of buildings in Naples adjusting the values to minimum and maximum.

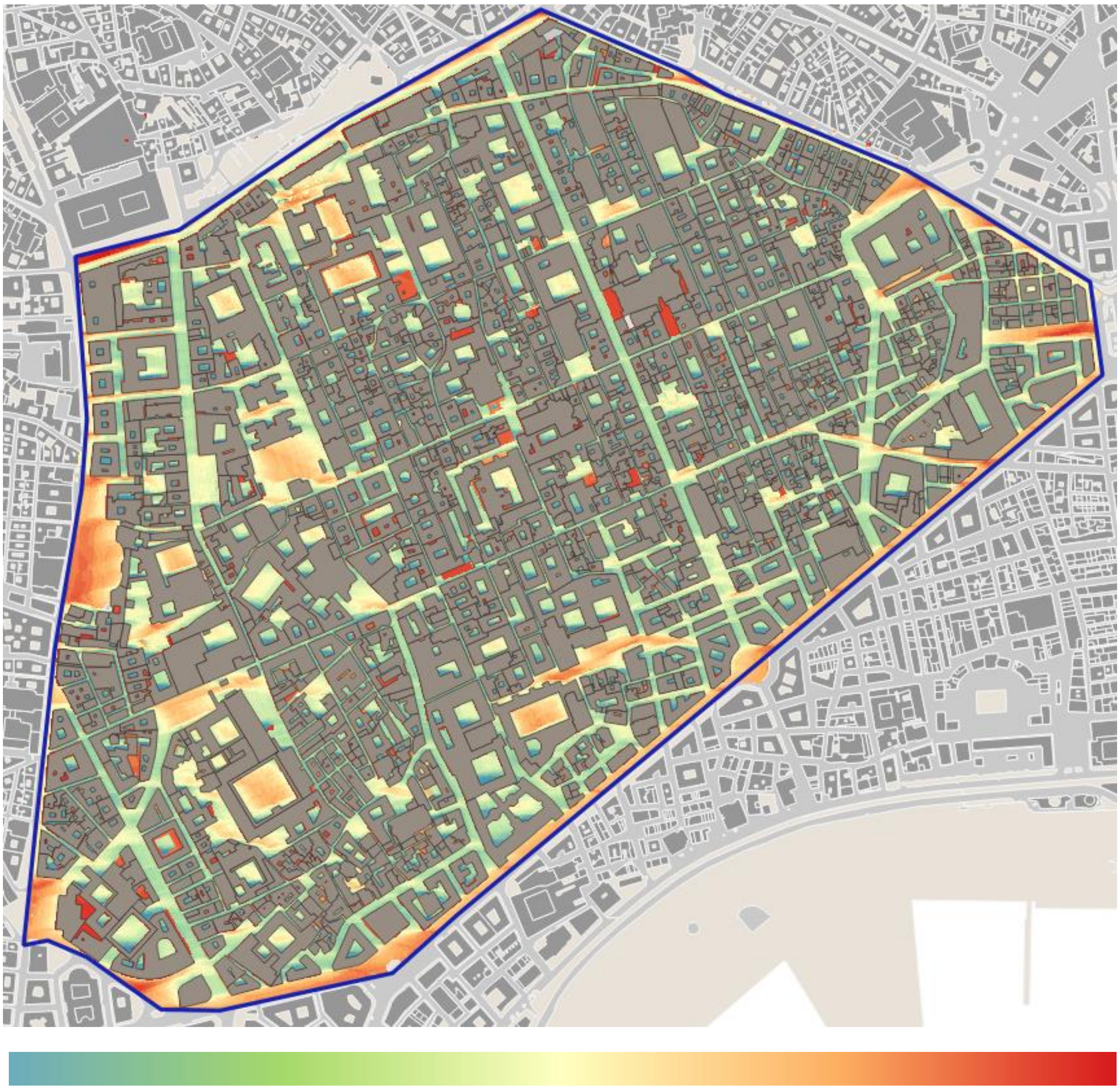
In the case of the public spaces, the vulnerability is calculated through the use of raster layers containing the sematic information. Because of this, the index is transformed to numerical values, for a better representation:



$0 < \mathbf{V_{N}0} \leq 0.2$	
$0.2 < \mathbf{V_{N}1} \leq 0.4$	
$0.4 < \mathbf{V_{N}2} \leq 0.6$	
$0.6 < \mathbf{V_{N}3} \leq 0.8$	
$0.8 < \mathbf{V_{N}4} \leq 1.00$	

Figure 91. Vulnerability of public space for the case study of Naples using numerical values.

In this case, the minimum value is 0.26 and the maximum 0.68, so the ranges where adjusted to this values to improve the visualization, resulting in:



$0.26 < \mathbf{V_N0} \leq 0.34$	
$0.34 < \mathbf{V_N1} \leq 0.42$	
$0.42 < \mathbf{V_N2} \leq 0.51$	
$0.51 < \mathbf{V_N3} \leq 0.59$	
$0.59 < \mathbf{V_N4} \leq 0.68$	

Figure 93. Vulnerability of public spaces in Naples adjusting the values to minimum and maximum.

5.4 Risk Assessment

Following the methodology developed in chapter 3, risk is calculated adding only the hazard requirement to the vulnerability calculation, since all study area has the same exposure (same situation as in Bilbao).

For this, the heat wave of the end of June 2022 was used as an example, as it was the most recent recorded for the area. This heat wave presented a maximum temperature of 38°C on the 27th of June. For the calculation of hazard indicators, the data from the weather station of Naples Federico II University, situated inside of the study area, was used. This station is in the southern part of the historic area and measures temperature, relative humidity and wind every 30 minutes, and the access to the data was requested to the university during the research stay of the doctoral thesis.

The heat wave went on for 3 days, from July 26th to 28th, with maximum temperatures over 34°C every day. The main data for the heat wave indicators is shown in Table 78.

	Heat wave data July 12-18th,2022				
	Maximum temperature	Thermal shock	RH	RH shocks daily	Duration
26th	34°C	12°C	63.2%	2	
27th	37°C	14°C	37.8%	2	
28th	38°C	14°C	45.9%	2	
Average	**36.33°C**	**13.33**	**48.97%**	**2**	**3 days**
Value for each indicator	**0.77**	**0.72**	**0.45**	**0.25**	**0.40**

Table 78. Data for the calculation of the indicators values for the hazard for the case study of Naples.

The final weight of the criteria and the hazard are obtained following the steps presented in chapter 3. The results are shown in Table 79.

	Criteria value	Weight	Hazard weight
Temperature	0.76	0.58	0.60
Relative humidity	0.39	0.19	
Duration	0.40	0.22	

Table 79. Calculation of the weight for the hazard requirement for case study of Naples.

5.4.1 Risk assessment

For the calculation of the risk index as shown in chapter 3, the levels for the hazard are stablished following three ranges:

- **H0** ≤ 0.33
- 0.33 < **H1** ≤ 0.75
- 0.75 < **H2** ≤ 1.00

As shown in Table 61, risk has different levels according to the hazard range and vulnerability of the element, from R0 to R5. Since the hazard has the same value for every element under assessment, the index for this case study is as shown in Table 80.

		Vulnerability: low to high				
		V0	V1	V2	V3	V4
Hazard	H1	R0	R2	R2	R3	R4

Table 80. Risk levels for the case study of Naples.

The results for buildings are shown in Figure 79.

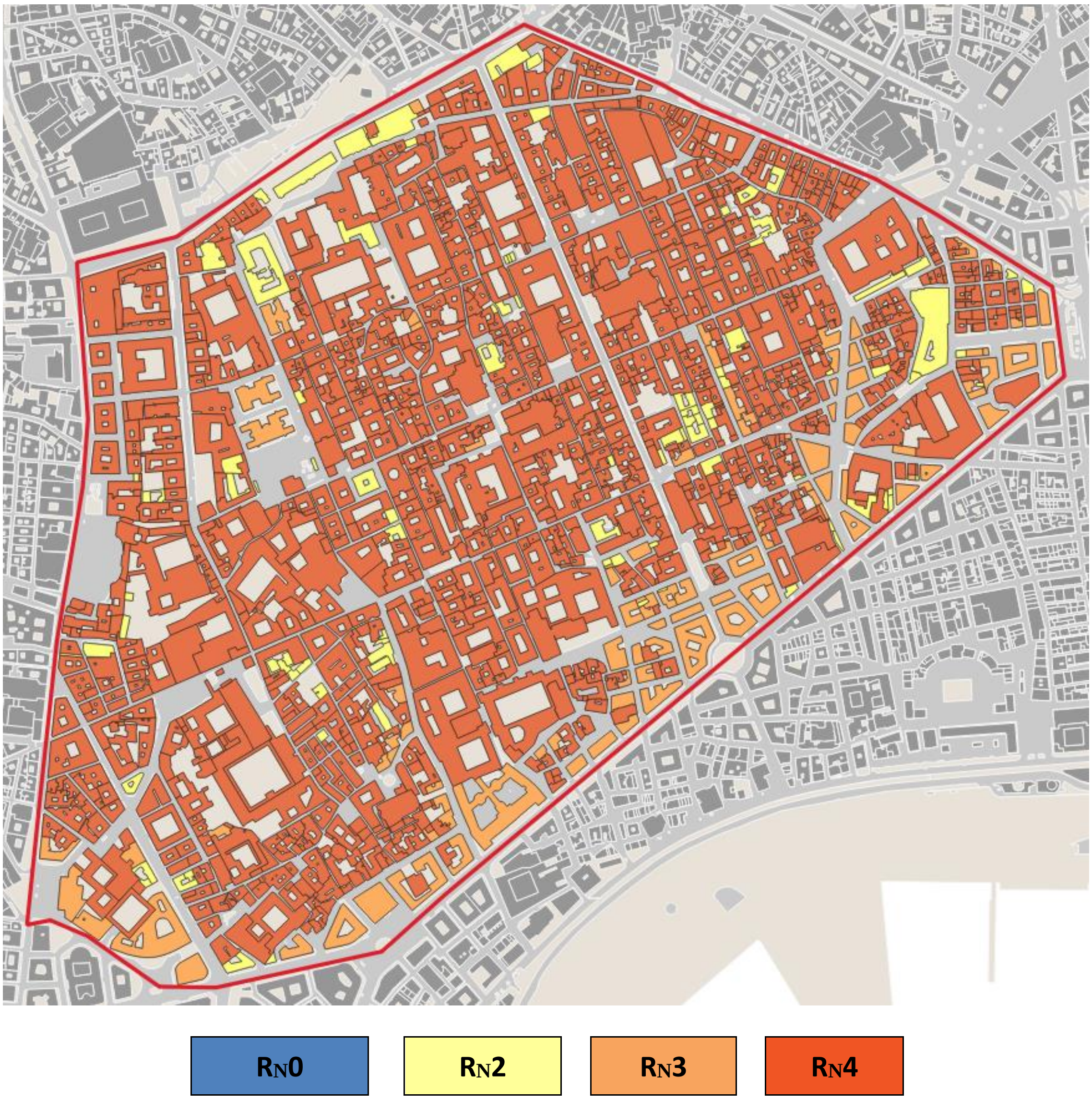
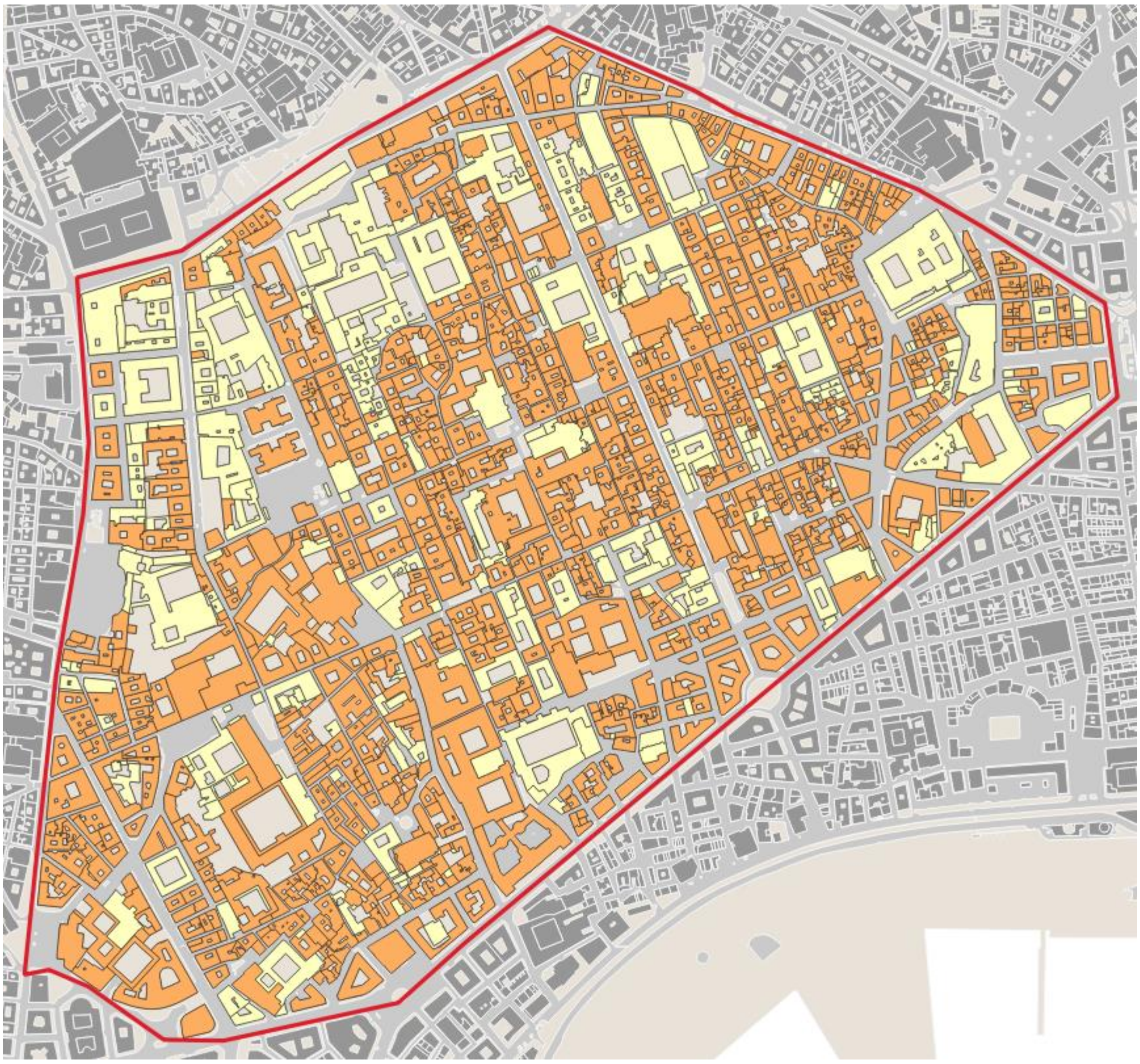


Figure 94. Risk for buildings in the case study of Naples.

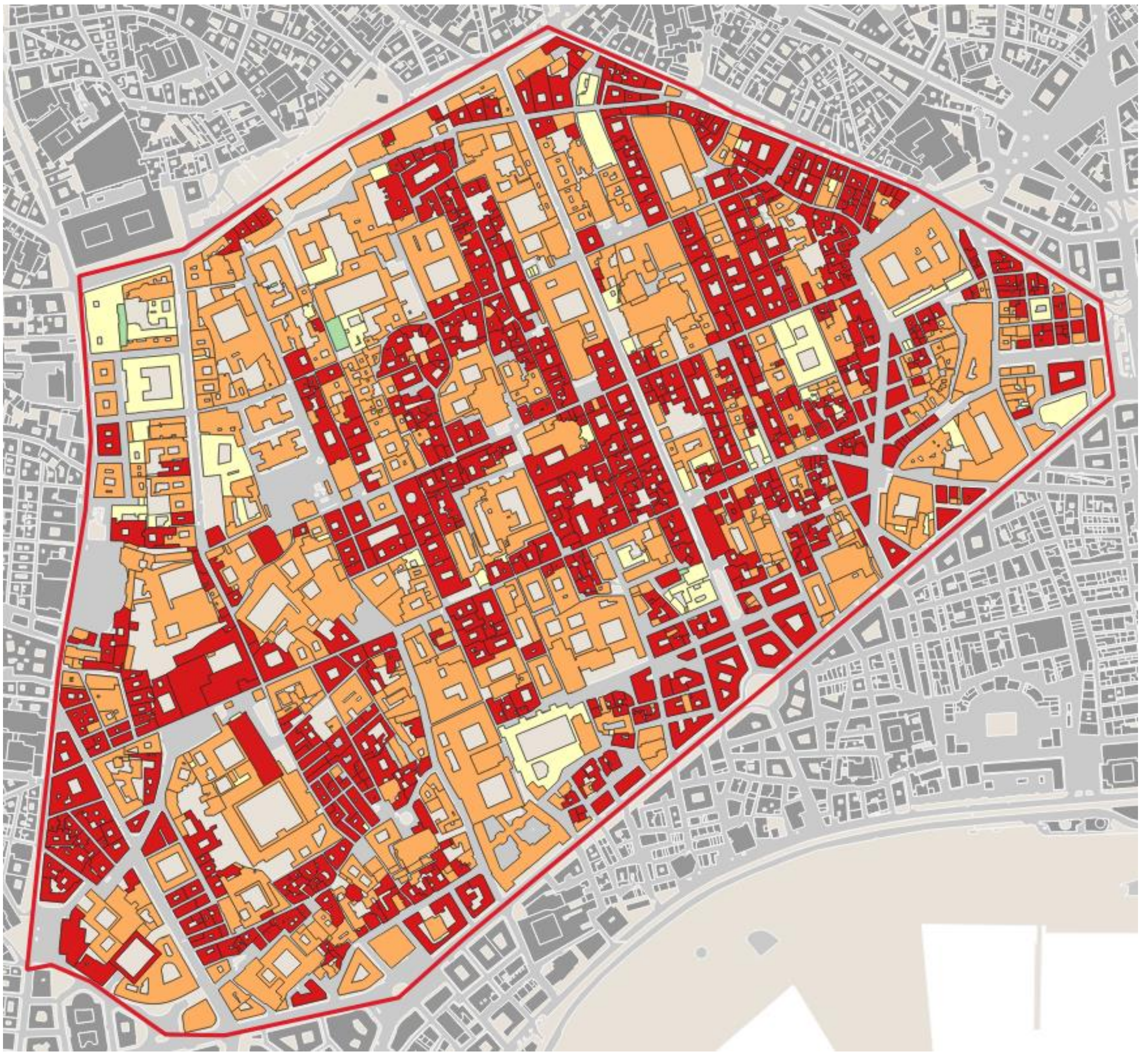
The visualization of risk using numerical values derived from the addition or risk to the hazard to the vulnerability and adjusted according to the weight of the requirements is:



$0 < \mathbf{R_N0} \leq 0.1$	
$0.1 < \mathbf{R_N1} \leq 0.4$	
$0.4 < \mathbf{R_N2} \leq 0.6$	
$0.6 < \mathbf{R_N3} \leq 0.8$	
$0.8 < \mathbf{R_N4} \leq 1.00$	

Figure 95. Risk for buildings in Naples using a numerical range.

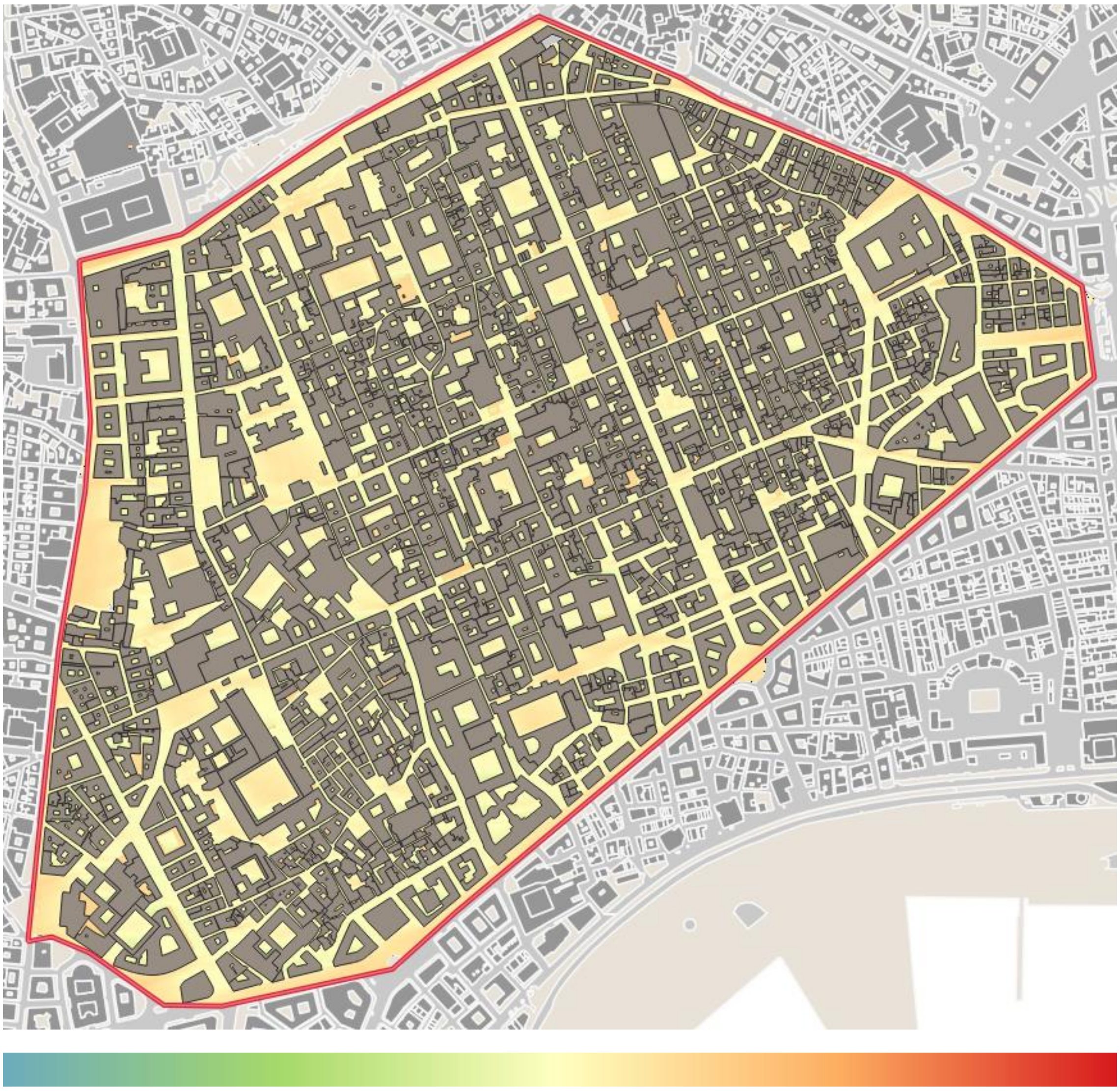
The minimum risk presented by the buildings is 0.36 and the maximum 0.69, therefore the vizualization range where adjusted with this values resulting in:



$0.36 < \mathbf{R_N0} \leq 0.43$	
$0.43 < \mathbf{R_N1} \leq 0.49$	
$0.49 < \mathbf{R_N2} \leq 0.56$	
$0.56 < \mathbf{R_N3} \leq 0.62$	
$0.62 < \mathbf{R_N4} \leq 0.69$	

Figure 96. Risk of buildings in Naples adjusting the values to minimum and maximum.

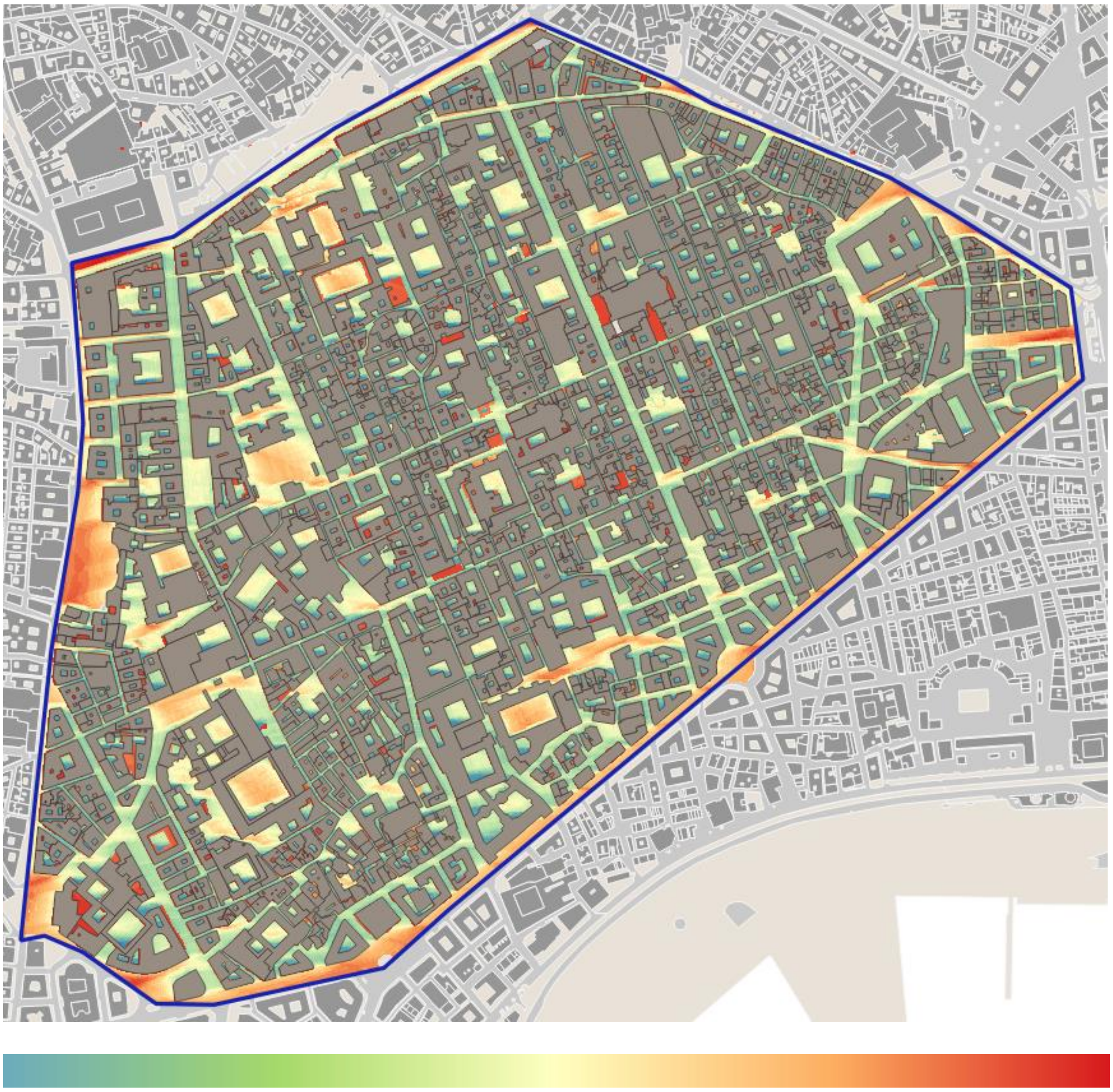
The risk for the public spaces is also converted to individual numerical values, using the weights assigned to each requeriment on chapter 3 (Figure 47).



$0 < \mathbf{R_N 0} \leq 0.2$	
$0.2 < \mathbf{R_N 1} \leq 0.4$	
$0.4 < \mathbf{R_N 2} \leq 0.6$	
$0.6 < \mathbf{R_N 3} \leq 0.8$	
$0.8 < \mathbf{R_N 4} \leq 1.00$	

Figure 97. Risk for public spaces in Naples using numerical value.

As the minimum and maximum risk values in this case is of 0.43 and 0.64 respectively, the final image is adjusted to these ranges:



$0.43 < \mathbf{R_{N}0} \leq 0.47$	
$0.47 < \mathbf{R_{N}1} \leq 0.51$	
$0.51 < \mathbf{R_{N}2} \leq 0.55$	
$0.55 < \mathbf{R_{N}3} \leq 0.59$	
$0.59 < \mathbf{R_{N}4} \leq 0.64$	

Figure 98. Risk of public spaces in Naples adjusting the values to minimum and maximum.

5.5 Discussion of the results

This chapter applied the prioritization methodology developed in chapter 3 to the case study of Naples, Italy. In this case, the categorization method was not applied and the full methodology was used with the available data.

As it was explained on the beginning of this chapter, due to data limitations and availability, the assessment for the public spaces was developed through raster images, adapting the methodology to the reduced number of available indicators. For this reason, the results cannot be assigned to each element, but are displayed with a gradient of colours for the whole network of public spaces. An accurate geometry layer for the open spaces and more available information on its geometry would have provided results closer to the reality of the area. Nevertheless, the application of the methodology through only the available layers of information provided a representation of its risk. Anyway, the model is open to the inclusion of further available data in the future, which would help to obtain more accurate results.

With reference to the buildings, the methodology was applied using their geometry as in the case of Bilbao. This time, most of the data for the indicators was available, and the results presented are closer to reality. As with the public spaces, the accuracy of the results depends on the availability of data to feed the indicators.

When calculating the risk, as it happened in the case study of Bilbao, meteorological data for the hazard calculation was only available for one station inside the historic area. Therefore, the hazard requirement is homogeneous for the whole area. The presence of more meteorological stations within the study area or in situ measurements would provide the specific climatic information in each location, leading to a more precise results.

The analysis of the results show that when using the index, 59 buildings resulted on a low vulnerability V1, 40 of a medium-low V2 vulnerability, 106 of medium, 62 of medium-high and 1091 of high vulnerability. When applying a numerical value the results show that a 95.73% of the 1,358 building have a vulnerability higher than 0.5, 23.19% of them higher than 0.7. In contrast, only 1 building is lower than 0.3 in vulnerability, with the 0.5% being lower than 0.4. These results are proportionate for the risk assessment, as the hazard value is homogeneous for the whole area.

5.6 Conclusions

For the validation of the methodology in Naples, 1,358 buildings were modelled along with the network of open spaces that comprises the historic area. The application of the full methodology resulted in an accurate representation of the vulnerability in the case of the buildings that could help the future prioritization of adaptive interventions. In the case of buildings and open spaces, a visualization of their vulnerability is provided, making possible the localization of the areas most at risk. It is shown in the results that because of the homogeneity of some of the indicators, as most of the buildings present similar characteristics regarding construction period and constructive characteristics, the social criterion and the solar radiation made the biggest difference when it comes to vulnerability levels.

The evolution of the historic area of Naples along the centuries and its organic growth through very different historic periods makes the data availability and accuracy a challenge. For the gathering of semantic information, the use of the general regulatory plan of the historical centre was used, through already defined categories for the buildings, to fill the information on construction period, materials, and protection level. As data for the public spaces was not available, other that satellite data and data calculated by the author, the assessment for the public spaces relied on a lesser number of indicators and its visualization had to be adapted to raster images, providing a different alternative to display the results. This made the results for public spaces not possible to differentiate by element, but to be shown as a gradient along the whole area.

The major difficulty in the case study of Naples comes from the data availability. The accuracy of the risk analysis highly depends on the availability of data and the complexity of the case study. Case studies size and regularity, from the building and planning perspective, has a direct impact on the complexity and, consequently, on the information gathering process. The lack of public data-bases requires manual information gathering and this manual activity turns into a tedious labour in complex case studies. A balance between accuracy and manual activity is fundamental. The methodology will show its highest potential when the available data and information can feed all the required indicators in the most precise way.

The methodology in the case of Naples was not applied with the categorization method, but using the full methodology. The risk was then calculated using the data from a station inside the historic area and managed by the Federico II University, for a recent heat wave of the end of June 2022. As with Bilbao, only data from one station was accessible, providing a homogeneous result for the hazard requirement in the area. More density of climatic data within the area or in situ measurements during the heat wave would provide more differentiated and accurate results.

6 Conclusions and future perspectives

Climate change is a fact and the consequent heat waves are a worldwide threat. Urban areas will face the challenges of their negative impacts on the built fabric as well as on the liveability of their inhabitants as climate change worsens and heat waves became more intense and frequent. As historic areas represent the sense of place and the identity of cities, being vessels for their tangible and intangible history, they deal with challenges that deserve special attention. Hence, risk and vulnerability assessment and their role on disaster mitigation and adaptation plans should be integrated in urban planning and conservation plans to confront the future challenges that climate change presents, and ensure a sustainable development of cities as well as a resilient built environment. Currently, the existence of vast databases, ensures the feasibility of vulnerability and risk analysis and enables planners for evidence-based decision making that will enhance holistic management and conservation strategies.

This chapter summarizes the conclusions that raised from the development of the thesis. Particularly, the methodology for vulnerability and risk assessment and its implementation on the two case studies. Thus, the conclusions will be divided between the methodological approach and its implementation. The chapter finishes with a proposal for future research and work to improve the existing knowledge.

6.1 Conclusions

Heat waves present a challenge in the field of risk assessment, especially when considering historic urban areas, as there is a gap in knowledge. As climate change and the derived hazards become more relevant, planning and conservation strategies will need to guide the adaptation of historic areas to face a more challenging future. Hence, the proper understanding of vulnerability and risk is a mayor necessity to prioritize and use adaptation resources.

6.1.1 Conclusions on the methodological approach

The risk assessment methodology presented in this thesis uses a comprehensive set of multidimensional indicators to understand the vulnerability and risk of buildings and open spaces to heat waves within historic urban areas. The methodology applies a holistic approach, gathering indicators from a physical, socio-economic, cultural and environmental perspective. These indicators are developed through a multiscale approach, taking into account the flexibility and replicability of the methodology.

A proper data management strategy is needed in order to obtain a robust and replicable methodology that ensures the interconnection between scales and the replication capacity. Data access for urban areas is complex and varies between case studies, especially in complex historic areas where availability of information is scarce and difficult to gather via fieldwork or other methods. The methodology should be, therefore, flexible to permit adjustments regarding data availability and updates over time, when data becomes available or adaptive actions take place. The latter would lead to a dynamic risk analysis.

In this thesis, a data model via GIS is proposed, which provides a base to structure and process the information from various fields, formats and scales in the historic area. This model provides the framework to structure geometric and semantic information in a coherent and interoperable way. This data can be stored and used for both building and open spaces, providing the assessment of every element of the historic area. Then, the MIVES methodology ensures that data from various sources can be measured comparably in an objective and easy way.

In conclusion, the methodology presented provides a robust and objective approach for assessing the risk of historic areas to heat waves,

6.1.2 Conclusions on the implementation on case studies

Data gathering and processing

One of the main tasks of the thesis was the gathering and processing of semantic and geometric information for the building of the GIS models for both case studies. This process resulted in the conclusion that data is still missing or not accurate enough in many cases, and this influences the results obtained by any data based methodology. In the case of geometric data, there is abundant resources when it comes to buildings, but the geometry of public spaces and their elements is missing from public data bases. Regarding semantic data, it varies depending on the case study, making the flexibility of the methodology a must to be able to adapt to different data constraints. When it comes to satellite and climatic data, there is not enough accuracy still for an assessment at building or public space scale. As with weather stations, only one measurement for the hole historic area does not provide enough data to provide different hazard values for the accurate implementation of the risk assessment. In the case of satellite data, some are still not downscaled enough for this scale of assessment, as for example, the NDVI data for

Naples, processed from Copernicus satellite data, was only available in a 300m grid, providing very homogeneous and not accurate inputs for the area.

The lack of certain data or its low accuracy made necessary more field work and manual development of data and geometry that reduced the automatization of the methodology. Nevertheless, an improvement in future data availability and accuracy would result in a much faster and efficient implementation of the methodology in any case study as the flexibility of the methodology guaranties its dynamic improvement.

Implementation on case studies and results

The methodology was implemented into two case studies with highly different dimension, morphologies and characteristics, Bilbao in Spain and Naples in Italy. Both historic areas where chosen to check the robustness and replicability of the methodology, as their complexity and data availability was very different. In Bilbao, some fieldwork was done to complete the data and the categorization method was implemented to check its reliability. Naples is a more complex historic area with a lot of data constraints, specially for the public spaces, so it was used to provide a different perspective on the replicability of the methodology. In this case the categorisation makes no sense and the fieldwork is an arduous work.

In Bilbao, of the 367 buildings that were categorized, 8 fell into a different vulnerability level using the categorization in comparison with the full methodology, all of them achieving higher vulnerability levels in the full methodology compared with the categorization. In the case of the public spaces, 87 where categorized and even if the vulnerability accuracy was very high, the categorization left out the most and less vulnerable elements, being the ones categorized all of the same level of vulnerability. Because of this, the results were completed with a numeric calculation of the vulnerability, in contrast to the one provided by the index. This concluded that the homogeneity among the urban spaces in a historic area makes small differences among the indicators, very relevant when calculating vulnerability, so the categorization method did not bring the most accurate results. In the case of the buildings, the results presented a very low margin of error, 2%, providing a good alternative to a full assessment with less data requirements, and consequently, resources in terms of time and cost.

The risk was then calculated for the area using a very recent and extreme heat wave of July 2022. This requirement applies homogenously to the whole area, as there is only data from one station. If more accurate data provided by a denser network of stations within the area or in situ measurements where available, this requirement could prove more accurate representation of the real situation within the historic area.

The case study of Naples historic area is, in contrast to Bilbao, much more complex, comprising 1358 buildings. Its evolution along the centuries and its organic growth through very different historic periods makes the data availability and accuracy a challenge. For the gathering of semantic information, the use of the general regulatory plan of the historical centre was used, through already defined categories for the buildings, to fill the information on construction period, materials, and protection level. As data for the public spaces was not available, other that satellite data and data calculated by the author, the assessment for the public spaces relied on a lesser number of indicators and its visualization had to be adapted to raster images, providing a different alternative to display the results. Consequently, it was not possible to obtain the results for public spaces element by element, but they were represented as a gradient along the whole area.

The methodology in the case of Naples was not applied with the categorization method, but using the full methodology, providing the vulnerability assessment for the whole area using the data for each element. The risk was then calculated using the data from a station inside the historic area and managed by the Federico II University, for a recent heat wave of the end of June 2022. As with Bilbao, only data from one station was accessible, providing a homogeneous result for the hazard requirement for the area. More density of climatic data within the area or in situ measurements during the heat wave would provide more differentiated and accurate results.

In both case studies the use of the vulnerability and risk indexes for the visualization of results proved not to be the most accurate, as when compared to numeric results, the use of a numerical ranges show more reliable representation. In this second case, the adjustment of the visual ranges to the minimum and maximum found in the area provided the best representation and visualization.

By applying the proposed full methodology, it is possible to obtain an assessment for both vulnerability and risk that can offer a diagnosis to help decision making. The data models can be easily updated and allow the incremental improvement of information, providing more accurate and dynamic results.

7 Future Work

The future of the research presented in this thesis is opened in a twofold perspective.

For the first path, the development of geometric and semantic data availability and accuracy would provide more accurate results and a replicable methodology. Although it is fundamental to balance the resources needed and the necessary accuracy, and in the case of this work this is achieved for the available and replicable data. Furthermore, an automatic acquisition and monitoring process could be implemented in the future in the data model. This inclusion of real time data or more accurate data would ensure a higher representativeness of the model, and the possibility for a dynamic digital-twin of the historic area that predicts risk caused by present and future climatic conditions. This could also extend usability of the model to the emergency phase, by the inclusion of real time data provided by temperature and humidity sensors. Including this data along with more accurate socio-economic, environmental and physical information could provide useful information for the managing of emergencies.

The second path is related with the next steps for the decision making process, that is, the extension of the model to include future downscaled climate scenarios and adaptive measures that are implemented, which would lead to a dynamic risk analysis. The research carried out in this thesis provides the first step for a decision making process when it comes to adaptation measures in historic areas: the diagnosis of the risky elements. This could be extended to the implementation phase of adaptation plans, by including solutions, adaptation measures and future climatic scenarios, as well as testing their impact in the model. The effect of adaptation solutions and strategies on the vulnerability and risk could be tested to evaluate their effectiveness and benefits, including, therefore, a simulation capability within the model.

This methodology and modelling strategy could also be extended to other urban areas, and applied on a bigger scale (city scale) to achieve an assessment at regional or national level. This could provide assessments and assist decision making at city, regional and even national scale that should be coordinated with major mitigation and adaption strategies.

Furthermore, to this possibilities, there is also a deeper understanding of vulnerability of historic materials to climate change and derived hazards that can be achieved. More detailed and accurate data could also provide research possibilities on the impact and behaviour of historic materials under different heat wave conditions, with humidity and temperature extremes that could help in the design of suitable conservation actions.

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