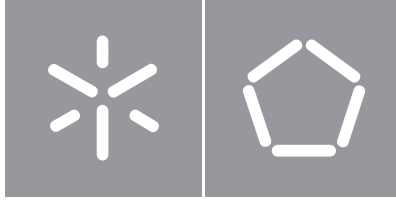




Universidade do Minho
Escola de Engenharia

Rafael Ramirez Eudave

**Towards an integrated vulnerability-based
approach for evaluating, managing and
mitigating earthquake risk in urban areas.**



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Doctoral Thesis
Civil Engineering

Work conducted under supervision of
Tiago Miguel dos Santos Ferreira
Paulo José Brandão Barbosa Lourenço

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Dedicatoria.

María, Fermín, Verónica, Héctor e Isabel: hogar y puerto;
Bech (†), Ricardo, Elisa, Areli y Marlène: puente y refugio;
Isis (y familia), Ósca, Carlos, Matea y quienes hicieron de Portugal una casa.
Gracias.

Ihcuac tlahtolli ye miqui

[...]
Quinihcuac motzacua
nohuian altepepan
in tlanexillotl, in quixohuayan.
In ye tlamahuizolo
occetica
in teoyotl, in tlacayotl,
in machi mani muan yoli in tlalticpac.

[...]
Ihcuac tlahtolli ye miqui,
occequintin ye omiqueh
ihuan miec huel miquizqueh.
Tezcatl maniz puztecqui,
netzatzililiztli icehuallo
cemihcac necahualoh:
totlacayo motolinia.

Miguel León Portilla.

Cuando muere una lengua

[...]
Entonces se cierra
a todos los pueblos del mundo
una ventana, una puerta.
Un asomarse
de modo distinto
a las cosas divinas y humanas,
a cuanto es ser y vida en la tierra.

[...]
Cuando muere una lengua,
ya muchas han muerto
y muchas pueden morir.
Espejos para siempre quebrados,
sombra de voces
para siempre acalladas:
la humanidad se empobrece.

Miguel León Portilla.

Statement of Integrity.

I hereby declare having conducted this academic work with integrity.

I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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University of Minho, Guimarães, may 2023

Rafael Ramirez Eudave

Resumo.

Sismos de grande intensidade, como aqueles que ocorreram na Turquia-Síria (2023) ou México (2017) deviam chamar a atenção para o projeto e implementação de ações proativas que conduzam à identificação de bens vulneráveis. A presente tese propõe um fluxo de trabalho relativamente simples para efetuar avaliações da vulnerabilidade sísmica à escala urbana mediante ferramentas digitais. Um modelo de vulnerabilidade baseado em parâmetros é adotado devido à afinidade que possui com o Catálogo Nacional de Monumentos Históricos mexicano. Uma primeira implementação do método (a grande escala) foi efetuada na cidade histórica de Atlixco (Puebla, México), demonstrando a sua aplicabilidade e algumas limitações, o que permitiu o desenvolvimento de uma estratégia para quantificar e considerar as incertezas epistêmicas encontradas nos processos de aquisição de dados. Devido ao volume de dados tratado, foi preciso desenvolver meios robustos para obter, armazenar e gerir informações. O uso de Sistemas de Informação Geográfica, com programas à medida baseados em linguagem Python e a distribuição de ficheiros na "nuvem", facilitou a criação de bases de dados de escala urbana para facilitar a aquisição de dados em campo, os cálculos de vulnerabilidade e dano e, finalmente, a representação dos resultados. Este desenvolvimento foi a base para um segundo conjunto de trabalhos em municípios do estado de Morelos (México). A caracterização da vulnerabilidade sísmica de mais de 160 construções permitiu a avaliação da representatividade do método paramétrico pela comparação entre os níveis de dano teórico e os danos observados depois do terramoto de Puebla-Morelos (2017). Esta comparação foi a base para efetuar processos de calibração e ajuste assistidos por algoritmos de aprendizagem de máquina (Machine Learning), fornecendo bases para o desenvolvimento de modelos de vulnerabilidade à medida (mediante o uso de Inteligência Artificial), apoiados nas evidências de eventos sísmicos prévios.

Palavras-chave: Aprendizagem de Máquina, Avaliação da vulnerabilidade sísmica; Avaliações de escala urbana; Avaliação do risco sísmico; Estruturas de alvenaria; Sistemas de Informação Geográfica.

Abstract.

Strong seismic events like the ones of Türkiye-Syria (2023) or Mexico (2017) should guide our attention to the design and implementation of proactive actions aimed to identify vulnerable assets. This work is aimed to propose a suitable and easy-to-implement workflow for performing large-scale seismic vulnerability assessments in historic environments by means of digital tools. A vulnerability-oriented model based on parameters is adopted given its affinity with the Mexican Catalogue of Historical Monuments. A first large-scale implementation of this method in the historical city of Atlixco (Puebla, Mexico) demonstrated its suitability and some limitations, which lead to develop a strategy for quantifying and involving the epistemic uncertainties found during the data acquisition process. Given the volume of data that these analyses involve, it was necessary to develop robust data acquisition, storing and management strategies. The use of Geographical Information System environments together with customised Python-based programs and cloud-based distribution permitted to assemble urban databases for facilitating field data acquisition, performing vulnerability and damage calculations, and representing outcomes. This development was the base for performing a second large-scale assessment in selected municipalities of the state of Morelos (Mexico). The characterisation of the seismic vulnerability of more than 160 buildings permitted to assess the representativeness of the parametric vulnerability approach by comparing the theoretical damage estimations against the damages observed after the Puebla-Morelos 2017 Earthquakes. Such comparison is the base for performing a Machine Learning assisted process of calibration and adjustment, representing a feasible strategy for calibrating these vulnerability models by using Machine-Learning algorithms and the empirical evidence of damage in post-seismic scenarios.

Keywords: Machine Learning; Seismic Vulnerability Assessment; Urban-Scale Assessment; Seismic Risk Assessment; Masonry Structures; Geographical Information Systems.

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Chapter 1

Introduction.

«Hic locus est ubi mors gaudet succurrere vitae».

This Latin phrase can be freely translated as "This is the place where death delights in helping life" and is still found at the entrance of the Anatomical Theatre of Padua (Italy) and some other similar facilities. The sense of this phrase is not only a reminder of the inevitability of death, but also recalls the due respect regarding the knowledge obtained from the mortal rests of human beings. There should be a strong ethical commitment when learning from losses, having a clear duty of giving better opportunities for the present and future generations. In this sense, is convenient to always keep in mind that our current knowledge related to seismic risk mitigation is based on processes of forensic engineering that have been built from material and human losses. This implies an ethical positioning towards the role of architecture and engineering in the context of human settlements. Therefore, the knowledge and observations obtained from past destructive events must be respectfully framed in the context of the human dimension of disasters.

* * *

Seismic events represent a very important challenge towards the protection and conservation of historical cultural assets. Some recent seismic events, such as the one that occurred in Türkiye-Syria (2023) and Mexico (2017), exposed the lack of preparedness and emergency planning that was reflected in the loss of human lives and large sets of constructions, including numerous historical constructions. The typical consideration of seismic risk as the convergent product of hazard (the seismic event, in terms of intensity), exposure (the elements prone to be damaged or lost as a consequence of the event) and vulnerability (the capacity that a certain element has to cope towards the event) reflects the critical relevance that proactive vulnerability assessments may have for mitigating damages and losses in post-event scenarios.

To undertake structural vulnerability assessments is not easy given a series of circumstances associated to the scale and specificity of historical cities. As an example, a relevant part of historical constructions in Mexico are catalogued and identified, but there is a generalised lack of the knowledge related to the structural safety of these buildings. Among the difficulties for performing structural assessments, it is convenient to remark the heterogeneity and variability of the structures, and the territorial-scale distribution of the samples.

Therefore, to perform straightforward and generalised assessments is still object of discussion and development. Despite the fact that some relevant advances have been reached for assessing punctual monumental-scale constructions, relatively small (often vernacular housing) assets are commonly out of the scope of these approaches. This situation was identified as a relevant gap in literature, closely related to a series of current situations that compromise the sustainability of historical urban environments and their inhabitants. The early and proactive identification of vulnerable elements throughout the historical constructions is a key step for mitigating adverse scenarios, primarily preventing human losses and also the occurrence of irreversible damages to cultural heritage. This objective is part of the sustainability and resilience of communities, as stated in the UNESCO Historic Urban Landscape approach.

Even if the discussion related to the conservation and protection of historical buildings is commonly focused on the cultural value of this assets, it becomes relevant to put attention on their role for satisfying human needs (namely housing, but also basic services) commonly adapted for local environmental conditions. Historical vernacular housing constructions typically reflect a construction tradition that encompasses a valuable source of popular knowledge for climatic passive technologies, structural solutions and habitat strategies. The loss of these material documents is also a loss of *genius loci*, that is often followed by a replacement process that implies overwriting the collective memory and identity.

1.1 Objectives.

This thesis addresses the insufficient knowledge in large-scale seismic vulnerability assessment methods for historical cities by presenting and demonstrating the suitability, robustness and potential of involving parameter-based descriptive models, digital data acquisition and management tools, geographical vulnerability-oriented databases and machine-learning based calibrations. Even if the practical examples have been implemented in Mexican cities, the experiences herein demonstrated can be extrapolated to other Historic Urban Landscape environments. A set of four blocks of specific objectives was outlined in order to structure the order and sequence of the topics herein explored.

1. **Descriptive models.** Configuration of a theoretical framework for holistic, accumulative, coherent and comprehensive semantic models for describing the Historic Urban Landscape. Design of suitable data models for urban-scale information, exploration of the state-of-art for urban-scale data acquisition, including the semantic codification (selection of descriptors) of vulnerability and risk.
2. **Data acquisition.** Proposal of robust frameworks for obtaining vulnerability-related indicators from multiple sources (e.g., catalogues, in-situ surveys, remote sensing tools, etc.). Configuration of a vulnerability-oriented survey based on parametric methods. Design of large-scale implementation strategies by the means of digital tools and distributed databases.
3. **Data framework and management.** Implementation of a Geographical Information System database with a series of vulnerability surveying-oriented extended capabilities. Design of an ad-hoc software for managing the vulnerability indicators in order to perform analyses and calculations. Distribution and publishing of the databases for supporting large-scale in-situ surveying and remote works.
4. **Seismic vulnerability assessment.** Performance of large-scale implementations by the means of the tools developed for supporting data acquisition and management. Identification of the limitations of the parametric vulnerability index method and proposal of calibration by the means of Machine Learning algorithms. Selected Mexican case studies in the States of Puebla and Morelos will be the base for performing seismic vulnerability assessments in the context of the 2017 Puebla-Morelos and Chiapas Earthquakes.

Figure 1.1 illustrates the relations existing among the thesis' objectives, the main subtopics and the content of each chapter. Each chapter is preceded by this same scheme in which the chapter's topics are shown in black, while the topics previously treated are shown in grey and those that are still not discussed are presented in grey with dashed lines.

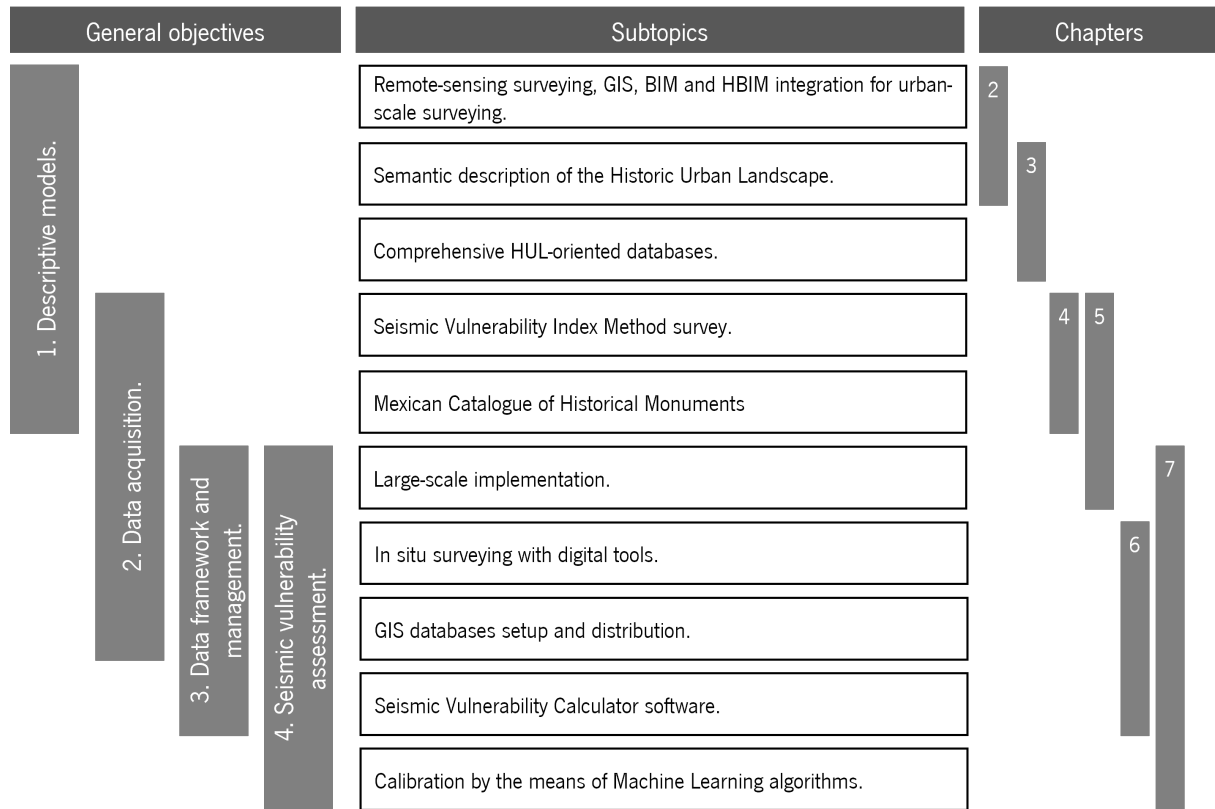


Figure 1.1: Schematic final representation of all the topics herein discussed.

1.2 Thesis outline and organisation.

This thesis has been organised as a sequence of chapters that have been conceived, consolidated and published as peer-reviewed journal articles, in accordance with the provisionat the School of Engineering of the University of Minho. The exceptions are **Chapter 1 (Introduction)**, since it is aimed to present a general view of the motivations and objectives of this research work, and Chapter 8 (Final remarks and future works) that highlights the main findings and potential further explorations based on this work. The content of the remaining chapters is herein integrally reproduced from the published version with minor editorial changes. Each chapter was conceived as an autonomous unit and, in consequence, there are texts, tables and references that appear more than once in this thesis. For the sake of consistency with the original conception, it was decided to present them integrally.

Chapter 2 (Vulnerability assessment of the Historic Urban Landscape) presents a literature review aimed to give a general theoretical frame on the descriptive codification of physical assets (i.e., cities and its systems and components), urban-scale data-acquisition procedures, levels of codification and vulnerability assessment methods. This chapter offers a first proposal for comprehensively model the historic urban landscape.

Chapter 3 (Comprehensive semantic descriptions for the HUL) delves into the theoretical discussion related to the representativeness and reliability of semantic models for constructions. This chapter offers a theoretical framework (that of the Aristotelian Causes) for building a categorised data organisation that includes the structural vulnerability descriptors, but is capable of virtually covering any other descriptor (social, economic, cultural) for becoming a holistic and reproducible data management system.

Chapter 4 (Existing Catalogues for seismic vulnerability assessment of historical buildings) analyses the potential that the existing Mexican Catalogue of Historical Monuments has for becoming an information source for performing vulnerability assessment procedures. In this chapter some preliminary findings are presented, namely those related to the representativeness of the semantic model towards vulnerability assessments, the accuracy of the fragility curves analytically obtained against the damages observed after the 2017 earthquakes and some limitations identified while performing the assessment for both data acquisition and management.

Chapter 5 (Vulnerability assessment of Mexican HUL: suitability and uncertainty analysis) Represent a large-scale example that integrates the previous tasks in the case study of Atlixco (Puebla, Mexico), in which more than 80 constructions were assessed. This exercise was primarily aimed to have a better understanding of the uncertainties and lack of representativeness of the approach. Nevertheless, the findings of this experiment lead to support the hypothesis of using the proposed method for Mexican historical urban environments. In this chapter, a strategy for uncertainties management is offered.

Chapter 6 (Implementation of Open-Source GIS databases for vulnerability assessment) explores the implementation of the vulnerability assessment approach in a dedicated Geographical Information System database that is subsequently distributed by the means of cloud-based services and open-source existing software, demonstrating the suitability of this approach for having team-distributed field surveys. It also presents the development of a Python language based software aimed to facilitate the database management while keeping the integrity of GIS layers. Furthermore, this chapter offers an alternative process devoted to the online publishing of the GIS databases for being consulted and distributed for edition.

Chapter 7 (Calibrating a vulnerability model with Machine-Learning and observed damages) represents a large-scale implementation of the full methodology in several municipalities of the state of Morelos (Mexico). A total of 167 constructions were surveyed and assessed in order to compare the damages produced during the 2017 Earthquakes in Mexico against the predictions obtained by the means of the parametric vulnerability assessment method. The uncertainties observed during on-site works are herein considered and discussed in order to offer feasible alternatives for including the epistemic uncertainty in the results. The parametric assessment approach is then enriched by using Machine Learning algorithms in order to enhance the representativeness of the model (i.e., redistributing the relative weights of the parameters), finding a suitable strategy for calibrating the method according to specific built environments (such as vernacular typologies and material homogeneity throughout a set of constructions). The findings of these experiments support the hypothesis of adopting the entire workflow presented in this thesis for assessing different and variate historical centres.

Finally, **Chapter 8 (Final remarks and future works)** highlights the main findings of this research, proposing a series of future research opportunities and framing the main limitations found during the entire research process. Annex 1 and 2 contain a summary of the criteria that was transversally followed for the application of the parametric seismic vulnerability index method among all the stages of this work.

1.3 List of publications subjacent to this thesis.

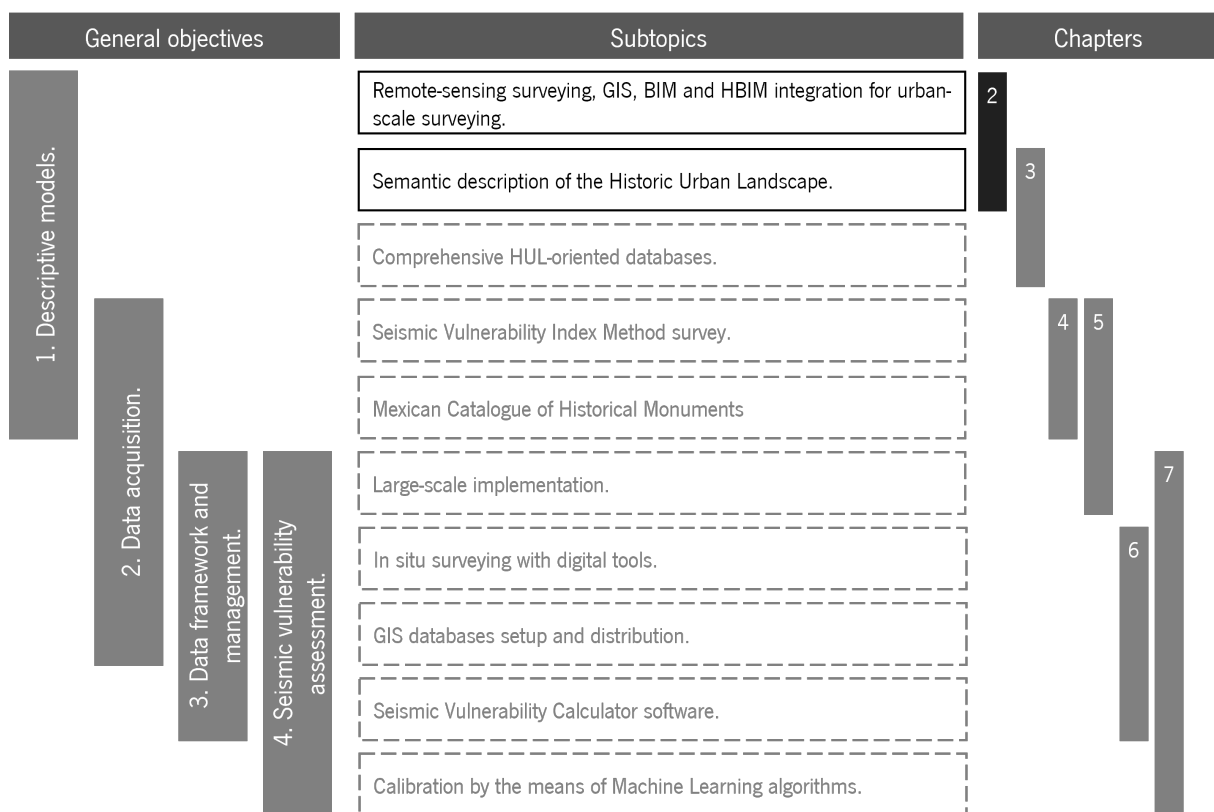
The following publications were the basis for this thesis' chapters:

- **Chapter 2.** Rafael Ramírez Eudave and Tiago M. Ferreira (2021) On the suitability of a unified GIS-BIM-HBIM framework for cataloguing and assessing vulnerability in Historic Urban Landscapes: a critical review, *International Journal of Geographical Information Science*, 35 (10), 2047-2077. <https://doi.org/10.1080/13658816.2020.1844208>
- **Chapter 3.** Rafael Ramírez Eudave and Tiago M. Ferreira (2021) Characterisation of the Historic Urban Landscape through the Aristotelian Four Causes: Towards Comprehensive GIS Databases, *Remote Sensing*, 13 (10), 1879. <https://doi.org/10.3390/rs13101879>

- **Chapter 4.** R. Ramírez Eudave and T. M. Ferreira (2021) On the potential of using the Mexican National Catalogue of Historical Monuments for assessing the seismic vulnerability of existing buildings: a proof-of-concept study, *Bulletin of Earthquake Engineering* 19 (12) 4945–4978. <https://doi.org/10.1007/s10518-021-01154-5>
- **Chapter 5.** Rafael Ramírez Eudave, Tiago M. Ferreira and Romeu Vicente (2022) Parameter-based seismic vulnerability assessment of Mexican historical buildings: Insights, suitability, and uncertainty treatment, *International Journal of Disaster Risk Reduction*, 74, 102909. <https://doi.org/10.1016/j.ijdr.2022.102909>
- **Chapter 6.** Rafael Ramírez Eudave, Daniel Rodrigues, Tiago M. Ferreira and Romeu Vicente (2023) Implementing Open-Source Information Systems for Assessing and Managing the Seismic Vulnerability of Historical Constructions, *Buildings* 12 (2), 540. <https://doi.org/10.3390/buildings13020540>
- **Chapter 7.** Rafael Ramírez Eudave, Tiago Miguel Ferreira, Romeu Vicente, Paulo B. Lourenço and Fernando Peña (2023) Parametric and Machine Learning-Based Analysis of the Seismic Vulnerability of Adobe Historical Buildings Damaged After the September 2017 Mexico Earthquakes, *International Journal of Architectural Heritage*. <https://doi.org/10.1080/15583058.2023.2200739>

Chapter 2

Vulnerability assessment of the Historic Urban Landscape.



Rafael Ramirez Eudave and Tiago M. Ferreira (2021) On the suitability of a unified GIS-BIM-HBIM framework for cataloguing and assessing vulnerability in Historic Urban Landscapes: a critical review, *International Journal of Geographical Information Science*, 35 (10), 2047-2077. DOI: 10.1080/13658816.2020.1844208

Abstract.

The use of digital representations of physical objects allows to simulate phenomena and predict behaviours. The representativeness of a model is based on the congruency between the code, the survey and the modelling strategies. In terms of physical space, two important approaches are the Geographical Information Systems (GIS) and Building Information Modelling (BIM). GIS approach is intended to code environmental information based on geographical references. BIM approach is intended to code buildings in terms of their components, generating parametric descriptions. For historic buildings, BIM extends to the so-called Historical BIM models (HBIM). Together, these strategies allow coding territorial-scale entities, such as historical centres. An application for these models would be the simulation of risk situations, leading to vulnerability analysis. Despite the existence of GIS-BIM-HBIM integration examples, most of their procedures are designed to fit with a specific case study, which questions the suitability of a general coding framework. This chapter presents a vision of state-of-the-art technologies and strategies for coding, surveying and model historical centres, with emphases on the analysis of urban vulnerability and risk. Finally, we propose a general comprehensive framework on the convergences of GIS-BIM-HBIM technologies and successful practices.

2.1 Introduction.

The analysis of any phenomena is linked with the codification and description of the different agents involved. To measure or to characterise an entity is, by itself, to code a physical feature into a conventional language (e.g., mathematical or semantic) in order to translate it into a model, able to be managed and operated. When analysing a determinate event, it becomes essential to establish methods, frameworks and treatments that permit to build correct assumptions and validate the results obtained through the corresponding analysis. The analysis of the vulnerabilities that a particular inhabited place has regarding specific hazardous events, such as fire, floods or earthquakes, needs accurate descriptions of the diverse objects that interact in a specific spatial framework. Then, the appropriate codification of the multiple entities involved in such a framework is thus the necessary background for a successful vulnerability assessment.

In order to approach an assessment for urban entities, it becomes necessary to establish how the urban entity needs to be described. In other words, the identification of the features that determine a specific condition of vulnerability as a whole. At the urban level, several elements may be intuitively identified as relevant for this description, such as streets, squares, neighbourhoods, green areas or transport networks. This semantic approach can be carried out in smaller scale, regarding individual constructions, namely buildings. The analysis of architectural objects is highly dependent on material and geometric descriptions. A successful codification of the physical information of a city (or a historical centre) may be the basis for constructing a model in which the identified attributes are reflected, and, in consequence, it becomes possible to test the hypothesis of the real world by using the model. In this context, it is fundamental to guarantee the consistency of the model (and its representativeness) and the variables of the studied phenomena.

Since the vulnerability of an urban entity is dependent on both environmental and anthropic elements, it becomes pertinent to explore the strategies and tools that are currently used to code those elements. A possible approach for coding anthropic phenomena is using standardised indexes and indicators common in social sciences for measuring poverty, marginalisation, level of income or inequality, for example. In terms of environment and natural geographic context, the existence of Geographic Information Systems (GIS) allows managing georeferenced information that determines a characterisation based on the spatial situation of a particular region. In the other hand, there is increasing use and interest in the application of the Building Information Modelling approach as a unified code for generating representative models of built entities, such as buildings and infrastructures. Furthermore, there is a recent interest on applying

this approach for generating models of existing structures and buildings, leading to the existence of the so-called Historical BIM or HBIM models, that can reflect specific singularities that are often found in historical constructions.

Contrary to what happens for the new ones, the process of modelling existing entities does not occur in a 'regular and well-behaved environment'. Historic buildings require sensitive approaches able to consider the active ageing of constructions, which are necessarily the result of multiple transformation, reparation, use and decay processes. These processes bring with them a series of physical prints that are meaningful for further interventions and diagnosis, such as deformations, cracks, strains or superficial decays. For this reason, when acquiring data, it is of paramount importance to adopt a comprehensive approach capable of incorporate the simplifications that are usually considered as acceptable when working with new constructions.

When addressed to existing constructions, some data acquisition technologies (such as satellite images or photogrammetric point clouds) permit to translate the physical reality in representative models. Nevertheless, there are some gaps in the interoperability of GIS, BIM and HBIM approaches, mostly because of the different primary purpose of the platforms. BIM, HBIM and GIS models can separately contain valuable information for analysing vulnerability. Finding ways in which the codes and models of GIS, BIM and HBIM approaches are consistent and interoperable may be the base of a comprehensive strategy for urban vulnerability assessment.

The existing challenges for this interoperability are, generically, four. The first challenge is to decide and establish what to code. Since the objects are real physical entities, they have virtually infinite attributes to be measured and characterised. The decision of what to code depends on which are the attributes considered as relevant for vulnerability analysis purposes. Secondly, it is necessary to decide appropriate data acquisition strategies. These strategies must be consistent with the information considered necessary, so the obtained data is reliable. The next challenge is related to the strategies for codifying the obtained information in models that can manage and reflect all the considered attributes namely concerning the interaction between different supports and software in which information has been coded and managed. Finally, it is essential to decide how to simulate the phenomena in order to assess the vulnerability of the represented object.

The present work will analyse existing literature in order to explore how the challenges mentioned above may be solved. It will show some recent discussions about the attributes that are considered relevant in a historical centre, i.e., which information would be essential to code. Then, it will show some current strategies that permit to acquire information from large-scale entities, such as photogrammetry and laser

scan surveys. Once the data acquisition is complete, it becomes necessary to code it into adequate models, so a discussion about the potential use and limitations of GIS, BIM and HBIM models will be held. Finally, the suitability of a comprehensive and integrative framework will be discussed. The hypothesis is that an adequate selection of semantic descriptors supports the acquisition of the semantic descriptions in order to generate representative models for assessing the vulnerability of the represented objects (see Fig. 2.1).

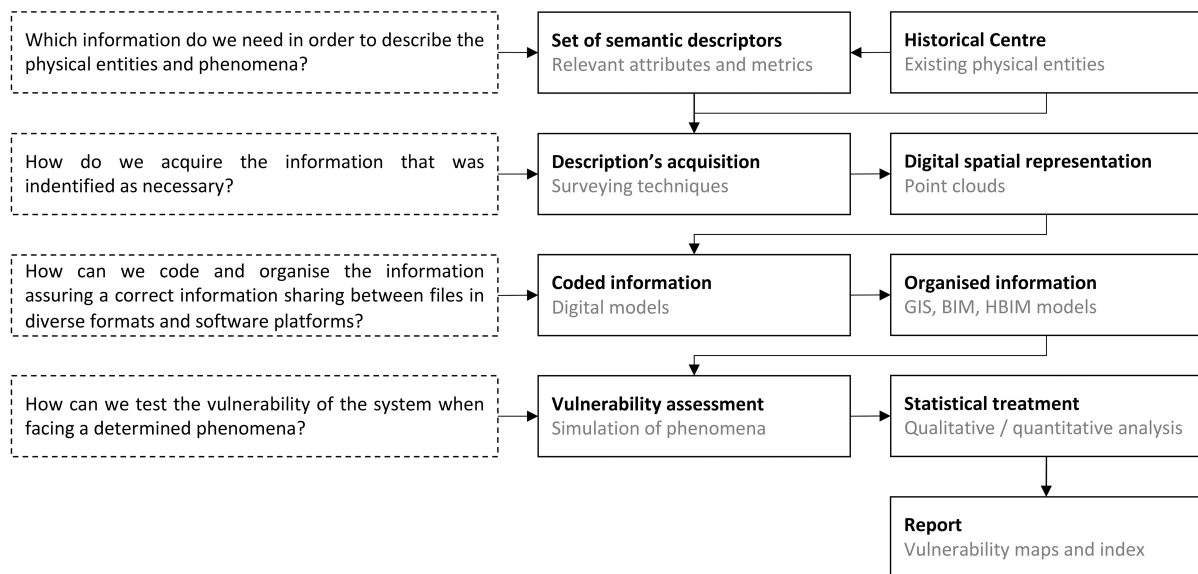


Figure 2.1: Summary of the main topics to be discussed.

2.2 Codification of physical entities.

The first important decision is what to code. The delimitation of the information that will be coded is based on both the phenomena and the entity that will be modelled. Then, when developing models for assessing the vulnerability of historical centres, it becomes fundamental to understand which are the attributes that the concept of «historical centre» implies. Moreover, an adequate delimitation of the phenomena and its components is needed. There is a relevant interdependency between the phenomena and the modelled object, in the sense that the success of the simulation depends on the consistency of the logic operations with the coded data. As a departing point, a semantic description is a base for further coding. Descriptors are, then, the generic features that will be measured in order to characterise a specific entity.

2.2.1 Codification of the Historic Urban Landscape.

There is no unique concept about what «urban» is. Despite this, there is a general agreement in considering that cities are shaped by a spatial context (with attributes such as size, density, distances or territories) as well as a social context, which comprises economic, social, political and historical processes [Boone and Fragkias, 2013]. The spirit of our present idea of heritage is strongly related to the relationship between intangible values and products concerning tangible entities in which these values are materialised [Bouchenaki, 2003]. Then, the concepts of «city» and «heritage» are often related. There is an increasing interest in cities through a holistic approach. One of the critical steps in this exploration is the concept of «cultural landscape», understood as the combined works of nature and of man [World Heritage Centre, 2010]. A relevant idea of the cultural nature of an anthropic landscape is found in ancient conceptions of the «genius loci», which refers to the uniqueness and authenticity of a city [Petzet, 2009].

One of the most recent efforts for providing international institutional frameworks for historical centres management and study is the development of the Historic Urban Landscape approach, supported by UNESCO. The HUL Guidebook [UNESCO, 2016], proposes that a Historic Urban Landscape is « . . . *the result of the historical layering of cultural and natural values and attributes, extending beyond the notion of 'historical centre' or 'ensemble' to include the broader urban context and its geographical setting. This wider context includes notably the site's topography, geomorphology, hydrology and natural features, its built environment, both historic and contemporary, its infrastructures above and below ground, its open spaces and gardens, its land-use patterns and spatial organisation, perceptions and visual relationships, as well as all other elements of the urban structure. It also includes social and cultural practices and values, economic processes and the tangible dimensions of heritage as related to diversity and identity*».

In order to characterise the city as a system, it becomes necessary to establish a functional description of it. Bambara et al. [2015] propose a city structural breakdown (Table 2.1) in which the urban complex is approached from four general subsystems, each one of them divided into two inferior level categories. Semantic descriptions of the elements that are found in a historical centre (mostly as a network of buildings and transitive spaces, namely streets) should include not only geometric and material parameters, but also valuable information about users (including their potential vulnerabilities) and occupation patterns.

There are precedents, such as Giuliani [2020], who proposed a spatial analysis based on a Space syntax representation. This approach considers two spatial properties, metric and topological, which permit to model physical space (namely urban space) as a network of flows that connect land uses. Then, this approach may enrich a set of semantic descriptors for streets and transitive spaces to be mathematically analysed.

Grade 1 category	Grade 2 category	Grade 3 category
1. Technical networks	1.1 Water 1.2 Power 1.3 Telecommunications 1.4 Transport	1.1.1 Drinking water supply 1.1.2 Sewage and stormwater 1.2.1 Electric network 1.2.2 Natural gas network 1.2.3 District heating system 1.3.1 Broadband 1.3.2 Landline telephone services 1.3.3 Mobile telephone services 1.4.1 Road 1.4.2 Railway
2. Housing	2.1 Mobile 2.2 Individual 2.3 Group	
3. Business	3.1 Services 3.2 Manufacturing Industry 3.3 Stores	
4. Public infrastructure	4.1 Decision-making crisis management infrastructure 4.2 Operational crisis management infrastructure 4.3 Infrastructure dedicated to vulnerable inhabitants 4.4 Other public services	4.1.1. Urban system administration 4.2.1 Police, emergency services 4.3.1 Health facilities (hospitals) 4.3.2 Educative facilities. 4.3.3 Prisons, retirement houses 4.4.1 Welfare benefits 4.4.2 Housing allowances 4.4.3 Business support 4.4.4 Record keeping 4.4.5 Legal and judicial facilities

Table 2.1: City structural breakdown proposed by Bambara et al. [2015].

Even if we generically accept that buildings are one of the multiple agents that conform the urban entity, it is useful to study them separately, since that single constructions may experiment more changes in time than the city itself and because there is an important variability in terms of solutions, typologies and systems that demand to be approached according to their singularity. Then, the building objects are, for historical centre semantic description purposes, considered as a subset of the historical centre entity.

2.2.2 Codification of single constructions for structural analysis purposes.

Structural assessment for historic structures is a challenging task, involving potentially significant uncertainties related to the mechanical properties of materials and the effect of different types of decay [Calvi et al., 2006]. Along with other aspects, these constructions are typically made of masonry, which brings multiple complexities to the process due to material heterogeneity, mechanical and geometrical non-linearities, weather/environmental related decay, among others. Nevertheless, there are several attempts for general

frameworks in which a set of assumptions is accepted, and it is possible, assuming some, to carry a simplified structural assessment. As an example, the Italian Directive [Consiglio dei Ministri della Repubblica Italiana, 2014] considers three different approaches for simplified seismic assessment by regarding the relation between the simplified assumptions that are taken against the detail and accuracy of the information available for a specific building. Each approach is considered as a Level of Valuation [Rondolini, 2018] and is associated with a certain kind of analysis (Table 2.2).

Level of Valuation	Description
LV1	Qualitative analysis and assessment of seismic safety with simplified mechanical models, which allows estimating a global vulnerability index.
LV2	Simple macroelement assessment (local mechanisms of collapse), based on the local response of macro-elements.
LV3	Complex analysis of the seismic response, namely through Finite Elements Analysis.

Table 2.2: Level of Valuation and their main features.

The application of the ‘Level of Valuation’ approach permits to have a general framework for analysing several buildings with similar typologies and construction technologies. This is especially useful when analysing historical centres, such as the case of Matera [D’Amato et al., 2020]. In the case of non-reinforced masonry, there are numerous works addressed to the characterisation of the most common failure mechanisms in order to use them as a starting point for assessing the tendency that a specific building can have to the activation of those mechanisms. This approach is mostly based on geometric parameters having thus critical limitations when dealing with heterogeneous and discontinuous (resulting from different construction stages) masonries.

The general idea behind this approach is to have a limited set of potential collapse mechanisms and a corresponding mathematical formulation in which a load factor may be found as a function of a set of geometrical parameters. It is relevant to remark that this approach has been developed specifically with the scope of non-reinforced masonry buildings. Some authors, such as D’Ayala and Speranza [2003] for example, propose abacus containing the most common failure mechanisms. A relevant work aimed at systematising a tool for applying the mechanism of collapse criteria can be found in the MEDEA (Manual for Earthquake Damage Evaluation and safety Assessment) project [Zuccaro et al., 2010], in which also reinforced concrete mechanisms of collapse are considered. When considering specific seismic characteristics of a determined region (more specifically, a historical centre), it becomes possible to have loss estimations based on past experiences [D’Ayala et al., 1997].

Both approaches, Level of Valuation and Collapse Mechanisms, are basically supported by geometrical information with very general assumptions regarding the mechanical behaviour of materials. Nevertheless, there exist also simplified approaches for analysing or categorising determined structural systems, such as masonry works. A remarkable approach is the Masonry Quality Index [Borri and De Maria, 2015], which permits to develop a semi-quantitative assessment of masonry constructions by taking into account attributes that may be visually identified. This approach permits to obtain indicative values for some mechanical properties of masonry walls based on simple-view features, such as the kind of plaster, the size and shape of the masonry units or the regularity and path of joints.

The definition of the attributes to be coded depends on the vulnerability assessment approach to be used. The above-mentioned ones – Level of Valuation, Collapse Mechanisms and Masonry Quality Index – permit simple assessments based on geometric and visual identification aspects. For such, it is necessary to establish a comprehensive list of parameters that can be used to describe the geometry of the main structural elements of a building (resisting walls, flooring and covering systems), as well as their state of conservation. Since the primary structural system of historical buildings is usually composed of masonry walls, most of the attributes should focus on the description of these elements. Some secondary attributes (typically obtainable through simple operations), such as slenderness or the relative area of the openings can be calculated directly in the databases. It should be noticed that there are some recent exercises focused on the automatic generation of these core elements directly from the raw point cloud data, allowing the creation of 3D models more easily and quickly [Thomson and Boehm, 2015].

From exposed, it is plausible to assume the possibility of performing simplified structural assessments taking simple geometric parameters as a base. A general geometric description may permit to characterise a determined construction in terms of an abacus of common failure modes. Furthermore, the existence of detailed images (e.g., from a photogrammetric survey) may even help to characterise a determined masonry work and some mechanical aspects.

2.2.3 Codification of vulnerability and risk.

The abundant concepts and conditions that are often related to the idea of risk may be difficult to define the true meaning of this concept. A valuable description is that of the international standard ISO 31000:2009 [ISO - International Organization for Standardization, 2009]. In this standard, the risk is stated as the «*effect of uncertainty on objectives*». Furthermore, uncertainty is «*. . . the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence or likelihood*». Objectives may consider a full set of aspects that are addressed to specific systems or components. In terms

of historical centres, those objectives may be related to the urban functions. In terms of constructions, targets may be the performance states. Risk is, then, the effect of uncertainty of achieving objectives due to potential events (or hazards) with a certain likelihood, regarding their consequences in a specific system.

Literature devoted to the multi-risk assessment of cultural assets offers numerous methodologies in order to describe hazards and vulnerabilities quantitatively. Most of these works are focused in specific contexts, frequently using a very local interpretation of risks. Since these exercises are generally developed for specific typologies, there is a lack of universal or generic evaluations intended to classify historical constructions. Several experiences use semi-quantitative rankings in which physical properties are related to numerical scales between the most favourable and unfavourable extremes. Another approach is to rate by the mean of gradients that are informatically computed [Eastman, 2005]. When several features are taken into account, it is possible to provide more complex vulnerability scenarios.

Some important cartographies that have been used in the bibliography as input information for vulnerability and risk assessment methodologies are:

- Seismic macro zonation and Peak Ground Accelerations maps [Augusti and Ciampoli, 2000];
- Elevation, slope and orographic traits [Agapiou et al., 2016];
- Urban mapping, land use and urban expansion patterns [Hadjimitsis et al., 2013];
- Demographic statistics [Tate et al., 2010];
- Sea erosion, salinity and coast exposure [Agapiou et al., 2016, Hadjimitsis et al., 2013];
- Soil erosion and landslide events [Agapiou et al., 2016, Skilodimou et al., 2019];
- Fires historical occurrence [Agapiou et al., 2016];
- Air pollution [Hadjimitsis et al., 2013];
- Proximity to roads and land communications [Hadjimitsis et al., 2013];
- Geological maps [Skilodimou et al., 2019];
- Precipitation data and flood events [Skilodimou et al., 2019];
- Cadastral maps and market prices mapping [van Westen et al., 2002].

The analysis of several hazard sources also aimed to develop multi-criteria approaches, in which natural phenomena are accounted and punctuated to establish prevention hierarchies and priorities. Some events are, however, conditioned for more than one layer of information. Tsunamis are a paradigmatic example of this. Also, the cartographies of specialised facilities and accessibility infrastructure are relevant for planning actions in case of emergency [Alzoubi et al., 2019], aiming to update proper strategies for post-disaster stages. The diverse outcomes of risk assessment can complement and feedback existing data or new cartographies.

In the context of seismic vulnerability for historic buildings, Augusti and Ciampoli [2000] propose the following definitions: «...*Vulnerability (of a building or other constructed facility): Sensitivity to actions in terms of damage. In rigour, given by the ensemble of the conditional probabilities of attaining of exceeding each level of damage (up to complete collapse), in function of the intensity of the relevant action; in practice, often measured by one or few parameters. Exposure: Existence of facilities subject to a hazard. Hazard: Probability of occurrence of an action (taking account of its intensity). Risk: Probability of damage/collapse (given by the convolution of hazard, exposure and vulnerability)*»

There is a broad spectrum of hazards to which cities are exposed to, even if they are unnoticed. Thanks to its generic nature, the framework presented in this chapter can be used to address most of these hazards, namely fire, floods or earthquake. However, due to their regional nature and high significant human, economic and social impact, special attention has been paid herein to the seismic vulnerability. According to the United Nations Office for Disaster Risk Reduction [2017], although earthquakes represented only 7.8% of disastrous events between 1998 and 2017, they are responsible for 56% of the deaths and about 23% of the economic losses resulting from natural disasters.

2.3 Data acquisition techniques.

Once the descriptors are established, it becomes necessary to design and execute proper data acquisition techniques in order to characterise those descriptors with reliability. The most recent and promising techniques for urban and architectonic surveying are based on the acquisition of cloud points to be treated and manipulated as three-dimensional spatial descriptions. The usual acquisition of these points is made through processes such as photogrammetry and laser scan, sometimes assisted with external devices for covering broad areas.

The representation of three-dimensional objects by means of point clouds is based on assuming that the physical surfaces can be represented through a sufficiently dense group of points that hypothetically tends to infinite. Then, a finite number of points is saved with information regarding relative or absolute spatial coordinates, which permits the spatial reconstruction of the object when assembling the sets of points. Those point clouds can be the base of further developments, such as generating surfaces and volumes through adequate processing. The most usual approaches for obtaining point clouds from physical objects are photogrammetry and laser scan [Lerma et al., 2013].

Two strategies top the list of the most used ones for urban analyses: the aerial vehicle assisted survey (which is an auxiliary tool for photogrammetric procedures) and the satellite images photogrammetry

[Manfreda et al., 2018]. A third powerful tool is the laser scan, which is still the most accurate surveying tool. However, it is yet unsuitability (or hardly applicable) for the acquisition of large-scale objects or extensive areas.

Some research groups have applied technologies like Virtual Reality to anticipate more accurate and faster survey campaigns [Lee et al., 2018], showing that a preliminary urban 3D model can be the starting point for a more profitable on-site survey.

2.3.1 Acquisition of point clouds from photogrammetry and laser scan.

Photogrammetry processes are based on the comparison of multiple photographic images, by using the camera as a «passive sensor». Even if the photographic image does not intrinsically contain information related with physical dimensions, the processing and comparison of a dense group of overlapped pictures permit to reconstruct the relative position of the points, given the optical features of the data acquisition device. This approach is relatively affordable but may need specialised personnel for post-processing the data. However, it is a very efficient strategy due to its relatively simple implementation. This technique is limited to the quantity and quality of the images for adequate processing.

In contrast, laser scan or LiDAR (Laser Imaging Detection and Ranging) can take active measures of surfaces, so each point is associated with its relative distance from the emission source, allowing to obtain very accurate and dense clouds. This capacity overcomes most of the limitations that photogrammetry has (namely its dependency on light conditions and the quality of the images). However, the relatively high cost of the devices can still limit the use of this technique. The most recent laser scan devices are even capable of obtaining colour information from the surveyed surfaces. The suitability of a strategy must regard constraints such as the on-site limitations and the availability of time and technical resources [Ahmed et al., 2011].

Despite the existence of other techniques and tools for obtaining point clouds, photogrammetry and LiDAR are still the most convenient means for data acquisition at the urban context, namely because of their suitability and flexibility in terms of scale and resolution. However, all strategies implicitly have to deal with challenges related to accessibility, cost and urban constraints. For instance, local regulations may limit the use of unmanned aerial vehicles under determined conditions. The experiment carried out by Russo et al. [2019] provides interesting perspectives for the use of low-cost and small aerial devices with relatively simple and cheap cameras for obtaining complete urban façades. This experience permitted to discuss and solve some of the technical constraints associated with this technique, contributing thus to the development of more accessible and economical workflows for urban-scale data acquisition.

2.3.2 Drone and satellite-assisted surveys.

The acquisition of point clouds with photogrammetry or laser scans can be enhanced if supported by another sort of devices such as Unmanned Aerial Vehicles (UAV) and satellite. Since one of the most critical challenges is related to the areas that must be covered during a survey, these tools permit to sweep large areas in relatively short periods of time. The selection of an appropriate tool might take into account the scale of the surveyed entity as well as the accuracy requirements. In several exercises, the scale factor is determinant when deciding the strategies for surveying a determined area [Roca et al., 2014].

In the last few years, there has been increasing use of Unmanned Aerial Vehicles, namely drones, to assist photogrammetry data acquisition. UAV offer several advantages when compared with traditional ground-level approaches, such as an excellent cost/benefit ratio. There is a rising range of vehicles and cameras that may be combined, as well as different processes for data acquisition and processing [Siebert and Teizer, 2014]. The quality of UAV-assisted photogrammetric surveys is mostly dependent on weather conditions and the limitations of the data acquisition system (cameras or LIDAR systems). Meteorological conditions might compromise UAV use in terms of stability when following specific flight paths. The design of an adequate workflow for preparation, recording, post-processing and data generation is needed (Figure 2.2). However, the use of aerial surveys may be combined with satellite and on-site control measures in order to enhance the quality and reliability of the acquired data.

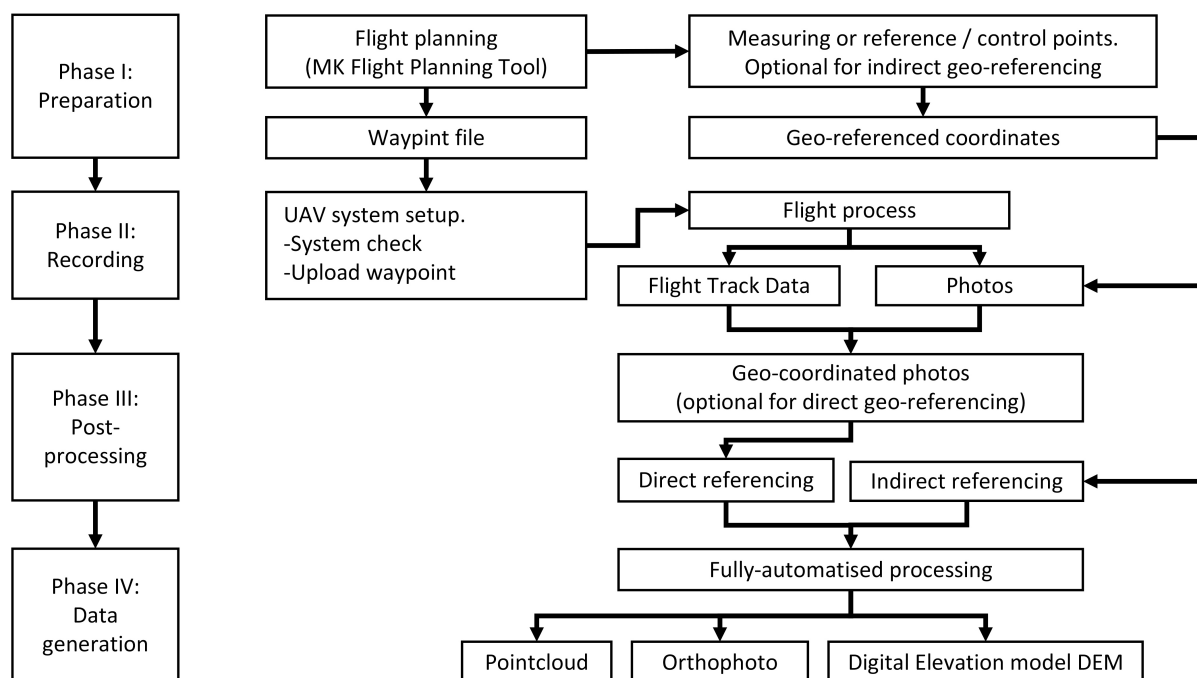


Figure 2.2: General workflow for a UAV-photogrammetric survey, based on Siebert and Teizer [2014].

Despite photogrammetry surveying is able to be carried-out with aerial (manned or unmanned) means as well as at ground level (close-range photogrammetry), the suitability of the strategy must be coherent with the surveyed area, the expected resolution and accuracy, the post-processing capacity and the application that the point clouds must satisfy (Table 2.3).

Feature	Photogrammetry (aerial)	Photogrammetry (Close range)	UAV photogrammetry
Planning Data acquisition/ Flight	Semi-automatic Assist-ed/manual	Manual Autonomic/assist-ed/manual	Automatic/manual Auto-nomic/assisted/manual
Size of the area	km^2	$mm^2 - m^2$	$m^2 - km^2$
Image resolution/ GSD	$cm - m$	$mm - dm$	$mm - m$
Distance to the object	$100m - 10km$	$cm - 300m$	$m - km$
Orientation	Normal case, recently also oblique	Normal/oblique	Normal/oblique
Absolut accuracy of the initial orientation values	$cm - dm$	$mm - m$	$cm - 10m$
Image block size/ number of scans	10-1000	1-500	1-1000
Special application (examples) and features	Large scale areas (mapping, Forestry, Glaciology, 3D City modelling) Aerial view	Small-scale areas and objects (archaeological documentation, 3D modelling of buildings) Architectural and industrial photogrammetry Terrestrial view	Small and large-scale areas (archaeological literature, 3D modelling of buildings and objects) Applications in inaccessible areas and dangerous situations Real-time monitoring

Table 2.3: Comparison between features of Aerial, close range and UAV photogrammetry [Hund et al., 2019].

The use of satellite images is a very interesting strategy for surveying inaccessible or large areas where the use of UAV is not suitable. However, this approach is limited to satellite images with a relatively high resolution, minor than 0.5 m [Gruen et al., 2003]. For this reason, it is convenient to have ground-level information for complementing satellite images, e.g., cadastral maps. It is possible to use Digital Surface Models (DSM) combined with satellite orthophotos and 2D maps (such as cadastral maps) in order to complete a general plan of a region. These images can be obtained by a steadily increasing – but still limited – number of satellite sources. A map got only from satellite images might be a right first approach, but there is still a significant amount of non-automatic work to do on the post-processing of pictures [Hund et al., 2019].

When architectonic typologies offer a limited universe of geometric hypotheses (e.g., roofs shapes), satellite images can also be used to fit objects into a limited list of choices [Flamanc and Maillet, 2008]. That approach is especially useful when it is possible to define geometric constraints that may be semi-automatically tested in the context of cadastral plans [Flamanc et al., 2003]. Specific urban survey experiences show that satellite images can be used to generate 3D models of dense construction complex [Maillet and Flamanc, 2004].

The use of laser-scan devices with terrestrial or aerial support may overcome most of the photogrammetric technique limitations since they do not depend on most of the environmental conditions that photogrammetry does. Besides, the use of laser-scan is not committed with as many «black boxes» as photogrammetry. However, data extraction and management require much more time and experience. Some researchers suggest that the suitability of both approaches may be decided according to the desired or expected detail on models [Gonizzi Barsanti et al., 2013]. Moreover, this decision must be taken by analysing the suitability of the relative comparative advantages of each technique (Table 2.4) in the context of the survey objectives.

Characteristics	Photogrammetry (Image-Based modelling)	Laser Scanner (Range-Based modelling)
Cost of the instruments (HW and SW)	Low	High
Manageability/Portability	Excellent	Sufficient
Time of data acquisition	Quite short	High – km^2
Time for modelling	Quite short, experience required	Often long
3D information	To be derived	Direct
Distance's dependence	Independent	Dependent
Dimension's dependence	Independent	Dependent
Material's dependence	Almost independent	Dependent
Light's dependence	Dependent	Almost/entirely independent
Geometry's dependence	Quite dependent	Independent
Texture's dependence	Dependent	Independent
Scale	Absent	Implicit (1:1)
Data volume	Dependent on the resolution of the images and the measurements	Dense point cloud
Detail's modelling	Good/excellent	Generally excellent
Texture	Included	Absent/Low resolution
Edges	Excellent	Quite problematic
Statistics	For each calculated point	Global
Open-source software	Some	A few

Table 2.4: Qualitative comparison between photogrammetric and laser-scan surveys, adapted from Gonizzi Barsanti et al. [2013].

2.4 Strategies for digital modelling.

The digital revolution changed multiple paradigms, including territorial management and urban processes. In this context, the role of specialised informatics approaches to territorial, urban and architectonic entities must be taken into account in order to assess their potential use and the integration of existing tools at the service of the HUL Approach. Once the descriptors of the historical centre have been established, and the consequent description of a determined historical centre has been acquired through the corresponding survey, it becomes necessary to organise this coded information by assembling a model. The different descriptors of a historical centre can be represented resorting to different approaches. Because the urban environment is continuously changing, the approaches or tools to be used must be flexible and easy to update. The Geographic Information Systems and Building Information Modelling are probably the two most used approaches for this purpose. Besides providing a flexible and easy to update environment, they allow covering a wide range of coded attributes, from the territorial scale up to the detailed building one.

2.4.1 The territorial scale: geographic information systems.

Geographic Information System (GIS) tools are a particular case of databases that works with geographically referenced data [Fischer, 1994]. GIS tools allow relating spatial coordinates with several layers of attributes, permitting to develop multiple mappings in a unified coordinated and referenced framework. GIS tools are collections of information about the real world, integrating semantic and geometric data for its analysis and applications [Wate et al., 2013]. A compelling ability of GIS is to document former urban configurations. This means that we are not only limited by the survey of the present state of the cities, but there is a framework to develop retroactive models that can receive historical hypothesis and add new data [Yang et al., 2019], helping to integrate a continuous narrative for historical centres. Other remarkable experiences are the use of GIS models in archaeological sites [Katsianis et al., 2008], which provide specific workflows that intend to understand cultural assets as an integral part of natural landscapes.

The attributes to be coded in a GIS database can come from different sources. The suitability of on-site surveys with proper documentation tools can permit to acquire accurate descriptions directly from the primary source. However, this process is constrained by the scale of the surveyed territory. For this reason, information must be acquired from territorial-scale three-dimensional models, and the use of automatic procedures to assist the process is highly relevant.

Some of the most recent efforts are addressed to recognising elements from point clouds obtained through laser scan or photogrammetric surveys [Pu et al., 2011]. Besides, automatic recognition of planes and surfaces might be the first approach to a series of entities that may be detailed in the next stages of the process, which may also be a suitable approach to adopt for the construction of preliminary urban models. The existence of simplified models can be easily enhanced by increasing some simple parametric exterior elements, such as windows or doors. Even if this process is carried with no automatic means, the use of techniques and tools such as photogrammetry or laser scan may provide detailed point clouds for generating 3D reconstructions [Dore and Murphy, 2012]. The automatic generation of simple customised elements (such as walls with openings) would permit the assessment of the most usual mechanisms of collapse for a wider number of constructions. Furthermore, those customised elements might be the base for the further development of BIM models. If some simple elements in façades are automatically recognised, then their attributes would be automatically stored in the database as well.

Geographic Information Systems (GIS) tools are massively used for mapping vulnerability and risk-related data, particularly those resulting from natural hazards [Hadjimitsis et al., 2013]. There is indeed an extensive list of parameters, typically used for evaluating vulnerability and risk, that may be mapped resorting to GIS tools [Tarolli and Cavalli, 2013]. Table 2.5 presents a list of some of these parameters for different natural hazards. Some examples are the Integrated Hazards Assessment Tools [Tate et al., 2011], the Mexican National Atlas for Risks [Ruiz Rivera et al., 2015] or the Portuguese IPMA (Instituto Português do Mar e da Atmosfera – Portuguese Institute for the Sea and Atmosphere) databases. In terms of global databases, some projects deserve to be highlighted in this context, such as the World Atlas of Natural Disaster Risk or the International Disaster Database [Shi et al., 2015]. Since GIS maps can combine or disable specific layers, it becomes possible to have sophisticated approaches in which chained events and dependent consequences are assessed [Department of Regional Development and Environment Executive Secretariat for Economic and Social Affairs Organization of American States, 1991]. There are several open platforms in which this kind of maps are available, most of them are developed and managed by public actors, such as governments and environmental agencies. This approach is crucial in the context of a multi-hazard risk assessment.

Hazard	Baseline data	Intermediate thematic information	Synthesis information
Earthquake	Epicentres	Maximum recorded intensity, magnitude	Seismic zoning (ground motion data, maximum expected intensity or magnitude, recurrence interval)
-	Fault lines	Frequency distribution and gap data	-
-	Plate boundaries	-	-
Volcano	Volcano location	Previous event impact	Potentially affected area (ash, lava, Pyroclastic flow, lahar)
-	-	History of eruptions	-
Hurricane	Landfall map	Previous event impact	-
-	Precipitation	Landfall frequency distribution	-
-	Wind	-	Hazard susceptibility
-	Coastal infrastructure	-	-
Landslide	Bedrock geology	Previous event impact	-
-	Slope	Landslide inventory	-
-	Vegetation	-	Design event (flood elevation and recurrence interval)
Flood	Precipitation	Previous event impact	-
	Streamflow	Maximum stream elevation	Hazard zonation
	Floodplain boundaries	-	-
Desertification	Soils	Ufezones	-
-	Precipitation	Aridity	-
-	Evapotranspiration	Erosion	-
-	Biomass production	Population density	-
-	Vegetation cover	Animal density	-
-	-	Land use	-

Table 2.5: Examples of baseline data for several hazards [Department of Regional Development and Environment Executive Secretariat for Economic and Social Affairs Organization of American States, 1991].

Besides natural hazards, anthropic phenomena can also be mapped, permitting to analyse hazard and exposure patterns contextualised with social indicators. If geographic databases are continuously fed with demographic and urban information, then it becomes possible to study disaster scenarios in terms of potential damages and losses in real-time [Silva et al., 2015]. Risk mitigation approaches can be integrally enriched by taking into account demographic information, such as vulnerable groups distribution [Tate et al., 2010]. Challenges due to global climate change are especially significant in the context of the real-time mapping and assessment of populated areas [Zerger, 2002]. The recent outbreak of the SARS-COV-2 virus is an example of how relevant are, for instance, human displacements models on the management

of sanitary contingencies [Research Urban Heritage Conservation and Sustainable Development Team, 2020]. There is a relevant opportunity while considering unusual actions (such as a territorial quarantine) in which the suitability of a determined city for sustaining a specific population, during a certain period of time, can be assessed as a limit state. There is exciting potential in having real-time GIS databases for analysing the availability of goods, stocks or vehicles, for example so there is optimal use of existing resources.

Whenever GIS databases contain layers of economic data, such as market prices and cadastral, potential economic losses can also be estimated and mapped. BIM models can be the source of several attributes (use, material, age, value, existing damages...) that can be meaningful in the context of specific risk situations [van Westen et al., 2002].

Amirebrahimi et al. [2016], tested how structural models in a GIS environment may help to identify specific damages that can be measured in terms of economic losses through the semantic nature of the construction entities. The exercise developed by Pelliccio et al. [2017] reached a finite element analysis from an urban model by using simplified assumptions. However, these assumptions are always able to be improved when new information is available and, in consequence, every new development is a meaningful investment of time and resources, and more accuracy is always obtained.

2.4.2 The modelling of constructions: BIM and HBIM approaches.

Building Information Modelling (BIM) is an integrated process based on creating digital models that represent a building through its entire lifecycle, by containing and relating different layers of information. Models are mostly composed of parametric instances and objects that incorporate reliable information from various sources, able to be managed by an interdisciplinary team [Strafaci, 2008].

Although BIM models are often related to 3D representations, this is only one of the possible outcomes of a BIM process. The instances and objects represented in models can contain information regarding financial, mechanical, procedural or energetic details. At the scale of individual buildings, the detail of semantic descriptors may reach the level of single elements [Brumana et al., 2019]. For this reason, BIM models constitute a shared tool for several professionals that work on the same project. There are significant efforts to standardise and create unified and standardised frameworks for BIM processes, such as the ones of buildingSMART, that continuously develops public data dictionaries and processes [European Commission, 2017].

One of the most attractive advantages of BIM process is the continuous development of an ultimate model from which it is possible to extract several real-time updated products, namely visual information. This way, every change is real-time updated in the related outcomes, which represents a significant saving of time. Besides, models can be fed with new information, meaning that the time used in their development is always an investment. The work of several specialists in the same model is possible because of the capacity of semantic enrichment, in which a determinate entity (namely components in a model) can store different layers of information meant for different operators. This also makes possible the interoperability of the same model with different platforms. Most of this semantical enrichment may be found in collective libraries that are continuously updated [Quattrini et al., 2015]. Semantic work also permits to set conceptual models in which all the relations between the single elements are explained and established.

BIM methodology is useful for modelling existing entities as well, such as historic buildings, permitting to document and analyse their current situation and to support future interventions. The adaptation of BIM methodology for representing the numerous singularities of the historic buildings led to the development of the so-called Historic Building Information Methodology (or HBIM), a term proposed by Murphy et al. [2009]. HBIM brings a series of additions to the traditional BIM approach aimed at overcoming some of the limitations inherent to the nature of the historic buildings. In general, an HBIM model is generated and organised following the same rules as a traditional BIM model. The main differences lie in the use of ad-hoc repositories enriched with historic architectonic and structural elements (due to their singular character against standardised and/or industrially produced ones) and the addition of data regarding deformations, decays and other sorts of damages, usually non-existent in new constructions. These decays and damages may be represented as parametric instances, which are meaningful and quantifiable in project processes, and programmed as adaptive components or additional properties of existing elements. These components are also allowed to retain metadata that can be useful in different processes during the intervention stage [Lo Turco et al., 2016]. Since HBIM models are expected to reflect the existing 'as-built' construction, conditions or pathologies (such as geometrical deformations and irregularities) should not be simplified or neglected.

When modelling an existing building, it is necessary to consider that several layers of information have a cumulative nature (since historic buildings are the result of multiple changes along its timeline). The model becomes a kind of «inverse engineering» product (Figure 2.3), with information directly acquired from the building (Figure 2.4). An accurate model can be used as a container for previous, present and future information, permitting to evaluate changes, damage processes, carry structural tests and even planning interventions with all BIM modelling advantages [Biagini et al., 2016].

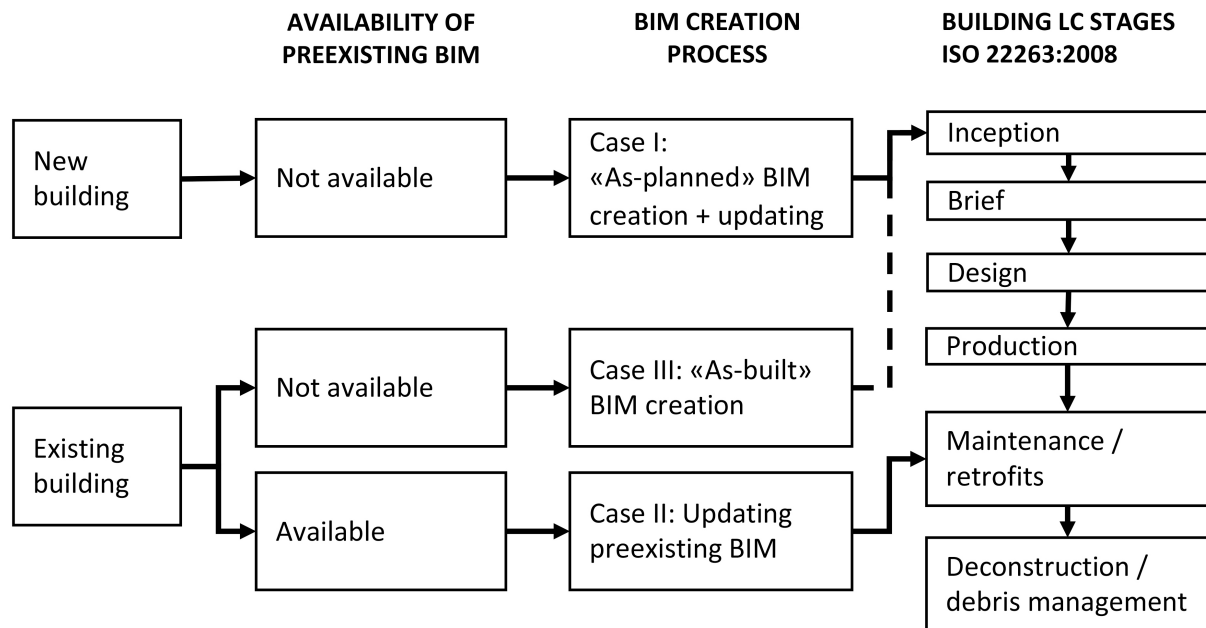


Figure 2.3: Similarities and specificities of BIM models developed to a new building or an existing one, based on Volk et al. [2014].

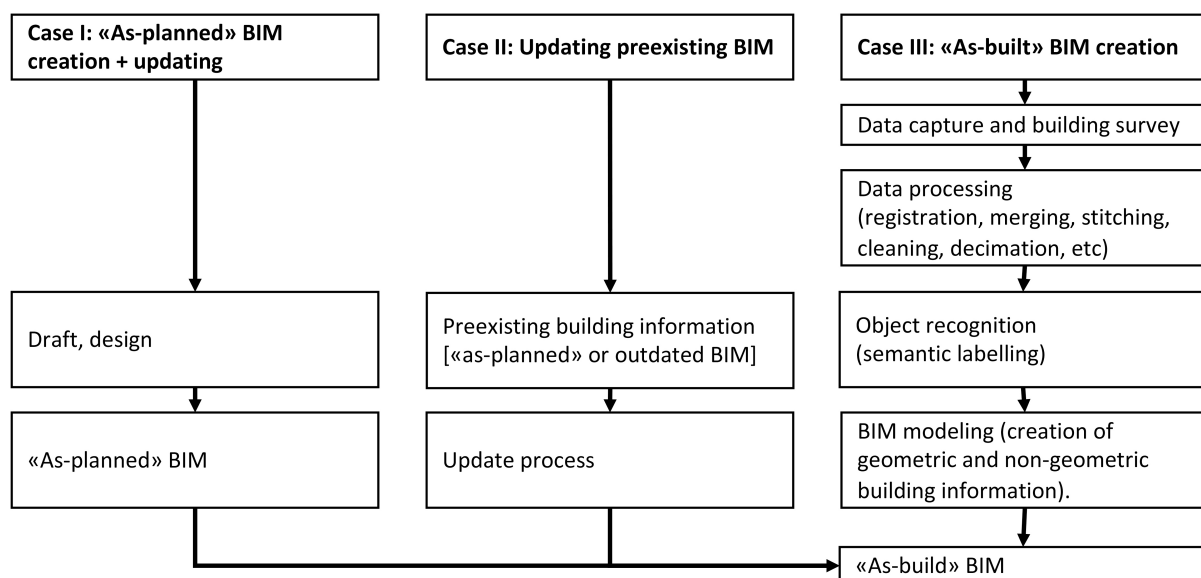


Figure 2.4: Typical BIM model workflows for a new building and an existing one, adapted from Volk et al. [2014].

HBIM models represent buildings by using libraries of architectural elements mostly based on several academic books on architectural history. Most of these elements have been developed in Geometric Descriptive Language (GDL), which permits to create complex geometries based on simple geometric primitives. However, numerous entities that are usually present in historic buildings (as vaults, specific kind of walls, arches, etc.) are not available in standardised libraries [Maietti et al., 2018]. Even if the uniqueness of every single building is still challenging, most appropriate steps can be taken in this field for

example, the adoption of standard terminologies for labelling and describing elements. Another feasible strategy is to use existing standard elements that may be later linked to details like pathologies, stratigraphic units or specific attributes that correspond to the uniqueness of cultural assets (for instance, by using the Industrial Foundation Classes or IFC format). This approach may be especially useful when working on open source platforms [Diara and Rinaudo, 2018].

The possibility of an automatic model generation directly from the surveyed information may imply a significant development in terms of wide-scale entities. Even if there are no consolidated tools for this purpose, several experiences have obtained promising results.

Rutzinger et al. [2009] tested the identification of wall patterns in urban scale by using a semi-automatic recognition of surfaces. This approach permitted to model entire urban façades and to classify some exterior features, namely windows and doors, adequately. Thomson and Boehm [2015] tested a semi-automatic process to directly transform information from a point cloud to a BIM model in small examples successfully. However, these recognition algorithms are not yet implemented in commercial software, and the accuracy of academic experimentation is still unsuitable (too low) for the production of HBIM models [Dore and Murphy, 2017]. Automatic identification of walls and façades can be especially useful when it is possible to make a clear typological identification. In that circumstance, it is possible to extrapolate spatial and construction specificities through the information obtained in an external geometric survey, allowing to estimate some post-disaster scenarios related, for example, with the amount of debris after a collapse or to prevent fire propagation patterns.

2.4.3 Experiences and challenges on GIS-BIM-HBIM integration.

At present, it is possible to use two-dimensional cartographies (namely GIS databases) in order to manage and store multiple layers of information and attributes. Many of the vulnerability-oriented attributes can be numerically stored in a simple 2D GIS database. However, even accepting that the data acquisition can be stored and managed under the basis of a 2D model, there is a great potential in the use of 3D cartographies to explore vulnerability-related phenomena determined by spatial conditions – for example, the study of air and water flow, the behaviour of volcanic ashes or solar incidences on façades. Although the use of 3D models for the extensive study of environmental vulnerabilities is still recent, it is a field in rapid expansion and with great potential for further development. An excellent example of the use of 3D cartography of the city of Sora can be found in Pelliccio et al. [2017]. Furthermore, the pursuit of developing 3D cartographies based on point clouds instead of the usual two-dimensional maps becomes useful for generating comprehensive documentation for the current state of an urban system. That three-dimensional

frame would permit to follow changes along the time and would even allow analysing disastrous events based on a well-documented precedent state.

Even if at their origin GIS and BIM approaches were conceptually different, there is an increasing interest in their interoperability. This would permit a careful control of complex projects, even when regarding small components of it, as well as its further assessment when regulations change. One of the most important differences that must be taken into account when working between BIM and GIS platforms is the level of detail that each system can represent and handle. While BIM and HBIM models are intended to represent a building as accurate as possible, GIS copes with larger scales and, consequently, with lower levels of accuracy. There exist, however, a normalised index where BIM, HBIM and GIS (among others) tools may be framed to share information [Matrone et al., 2019]: the Level of Detail (LoD).

Level of Detail (LoD) is the name of a discrete scale in which five different levels of representation are described by regarding the balance between reliability and simplification that may be assumed in a specific model [Biljecki et al., 2013] (Table 2.6). However, data acquisition is also a constraint that determines which LoD can be reached from the primary source. In general terms, the descriptors for these Level of details are those presented in [Biljecki et al., 2013].

LoD and Features			Aerial Acquisition		Terrestrial Acquisition	
LoD	Abstract Feature Representation	Distinct Features Identified	Satellite Photogrammetry	Spaceborne / Airborne	Close-Range Photogrammetry	Mobile Laser Scan
0	Digital Terrain Model (DTM)	Buildings footprints	Yes	Yes	-	-
1	Digital Surface Model (DSM)	Buildings as prismatic	Yes	Yes	-	-
2	Building Structures with prototypic features	Prototypic roof shapes	-	Yes	Yes	Yes
3	Buildings with architectural features	Openings and textured wall surfaces	-	-	Yes	Yes
4	Buildings with interior architectural features	Rooms with interior furniture and texturing	-	-	-	Yes

Table 2.6: Matrix for different 3D modelling techniques and representativeness, adapted from Wate et al. [2013].

Thanks to LoD definitions, it is possible to insert simplified BIM entities in GIS models. Nevertheless, those simplified BIM models can be linked with more complex representation (as external references), through a controlled decrease in their level of detail. Such a decrease can be done by following specific LoD definitions, as the CityGML ones [Deng et al., 2016]. Another feasible strategy for interoperability is the sharing of geometrical information between IFC and CityGML standards. An IFC solid object can be mapped to a set of surfaces that jointly permit to describe the solid semantically. However, this sharing may be problematical concerning the orientation of the surfaces. To extract the geometrical parameters of an IFC entity, it becomes necessary to filter the IFC classes in order to extract only mappable surfaces [Donkers et al., 2016]. At present, experiences such as the one of Cecchini [2019] demonstrate the suitability of downgrading a BIM model to simplify some geometric parameters of IFC instances, allowing CityGML standards-based entities reconstituting volumes from sets of surfaces.

There are some examples in the literature – see for example Deng et al. [2016] –, where CityGML was chosen as a key schema in an instance-based method for generating mapping rules between IFC and CityGML. In this way, it is possible to generate a so-called Semantic City Model, which captures relevant information from BIM and GIS models, achieving automatic data mapping in different Levels of Detail. An in-depth exploration of the issues about the integration of BIM and GIS carried by Ohori et al. [2017] describes explicitly geometric and topological processing problems (mostly because of self-intersection inconsistencies) and incorrect georeferencing of IFC models, concluding that most of the errors are caused by source errors when developing BIM models. Since the conversion between data models usually leads to data loss, some authors have already proposed strategies to guarantee information coexistence by establishing references between the IFC and CityGML standards, see for example Cheng and Deng [2015].

It is pertinent to recall that the LoD is addressed to the granulometry of the information for representation purposes. Hence, it is possible to have an LoD 0 model with multiple data fields describing, for instance, three-dimensional attributes of the construction, even if they are not graphically represented. This means that such models (even low LoD models) can store the attributes required to feed simplified vulnerability assessment methodologies. In the other hand, a detailed model would be the base for more complex approaches. For example, a very refined LoD 4 model would precede a corresponding Finite Element Model, or an LoD 3 model would provide data for carrying a Masonry Quality Index [Borri et al., 2015] analysis. Hence, the limitations and needs of using a certain Level of Detail as a standard for vulnerability assessment purposes depend directly on the characteristics of the assessment approach to be used. When a BIM model already exists, it is possible to extract or filter input data to simplified models, preserving intact the original information.

The transition from 3D models to CityGML requires converting both geometric and semantic information. Despite the existence of some successful experiences [Dore and Murphy, 2012, Kokla et al., 2019], there is still a significant challenge associated with data sharing between BIM and GIS platforms. Some works, like the one of López et al. [2018], propose complete workflows for covering a wide variety of scales. Recent experiences have successfully demonstrated that HBIM-GIS integration is possible and useful – see, for example, the case of the ‘Gran Torre di Oristano’ [Vacca et al., 2018]. There are interesting works in the literature intended to automatically label urban elements with semantic concepts [Cordts et al., 2016] by using ground-level photographs. Furthermore, there is also recent literature addressing the possibilities of automatic and semi-automatic identification of objects directly from satellite images [Zhu et al., 2017].

A complete three-dimensional model can offer valuable information about materials and geometric aspects of the structural elements. This may constitute a first approach to estimating tensional states in the whole structure, permitting to develop simplified structural analysis [Pelliccio et al., 2017], as well as roughly estimate the energy needed to activate diverse mechanisms of collapse, e.g., partial or global façade overturning. Once a simple model is obtained (i.e., a general urban model), the single entities can be enhanced with further surveys and detailing. This might permit to perform a first-contact study of the elements that have been identified as the critical ones. Such elements might be further assessed through BIM modelling and even reaching the design of accurate finite element models. However, this enhanced model may still be linked to the original urban one. This capacity permits to have a phased project in which some parts are more detailed than others.

Since HBIM models are a particular case of BIM, the generalities for their integration in a GIS environment would be applicable for both. However, it is important to keep in mind that HBIM models can represent physical decays that might be related to multiple environmental phenomena, such as water flows, wind, solar incidences or presence of vegetation, for example. Hence, the generation of proper links between environmental information in GIS databases and specific decays in HBIM models suggest a promising opportunity for the assessment and diagnosis of vulnerabilities, finding valuable correlations. Some researcher tried to deduct the decay process of a building by comparing an as-built and an idealised model. Nieto-Julián et al. [2020], for example, propose to build a purely theoretical model based on documents and historical research; and a second one that reflects the real current state of the building through geometric data obtained with laser-scan or photogrammetry techniques. This permitted to differentiate some aspects that may be part of an original conception or a process of decay.

Although the GIS-BIM-HBIM integration is relatively recent, some experiences reported in the literature reveal promising uses and potential opportunities in the field of management and protection of built heritage. Campanaro et al. [2016] discuss the use of a 3D-GIS model of a building in Pompeii to collect information about decay processes in the building's façades – such as cracks or lack of verticality –, which is then used for mapping an overall risk indicator. Even though this experience did not include the integration with BIM environment, the processes generated by using the ArcMap and ArcScene modulus can be developed in BIM environments as well. De Ruvo [2019] also explores the suitability of the interoperability of HBIM-GIS frameworks in the cities of Quinson, Tolentino and Venice. It considers, among others, its usefulness in the representation of risks and hazards, considering the risk analysis in the context of the ResCult project. Another noteworthy example of the GIS-BIM-HBIM integration was developed by Pelliccio et al. [2017] for the Italian city of Sora. In this work, the authors use a comprehensive BIM 3D model for testing diverse environmental agents related to physical decays, including wind, solar incidence and water flow. In this specific case, the vulnerability analysis is concentrated in a limited part of the historical centre of Sora. However, the works mentioned above suggest that the use of GIS platforms for integrating multiple BIM models might also help to ensemble and frame a regional model.

Another relevant aspect is related to the storage and management of the files that represent intermediate steps before the feeding of the GIS database. The GIS database would be able to be fed from different sources, such as on-site surveys and from data extracted directly from BIM-HBIM models by using a proper interface. Expectedly, the origin of BIM-HBIM models might be variable, since there is a vast number of actors interested in their creation and update, namely contractors, designers, government instances or academic institutions. Hence, it is possible to admit that the storage of BIM-HBIM models (as well as their background sources, such as point clouds) would be independent of the GIS database, only generating temporary links for feeding the database, which may be done by using cloud informatics services, for instance. Then, a preliminary design might consider an online cloud-based database with a distributed storage of the sources.

2.5 Vulnerability assessment methods.

A vulnerability analysis of a historical centre is typically aimed at considering the effects of a determined event into this system. If the models of both historical centre and phenomena are representative, then it is possible to predict the interaction of the event and the system with a certain grade of reliability. The effects must be compared with a pre-established acceptability criterion in order to assess the need and

magnitude of mitigation. The disruption that the system may suffer as a consequence of the selected event can be studied through qualitative and quantitative analytical tools, for instance, Risk Matrix, Failure Mode and Effect Analysis (FMEA), Failure Tree Analysis (FTA) or Event Tree Analysis (ETA).

2.5.1 Risk matrix.

A risk matrix is a semi-quantitative tool that allows relating the likelihood of a determined event against the expected effect that may have on the system, expressed in levels of severity. Different risk matrices can be constructed for a specific historical centre by confronting the relative frequency and intensity of past events that affected it, with their effects on the system.

The acceptability of risk [Vrijling et al., 1998] is also addressed to determine the threshold from which a particular assumption of risk becomes reasonable. This is not only useful for assessing existing systems, but also for targeting performances and enhance specific aspects of the system. In terms of structures, for instance, this target safety [Holicky et al., 2015] is closely related to the existing codes and performance states.

2.5.2 Failure mode and effect analysis.

In the context of risk assessment, one of the most relevant techniques for failure analysis is that of Failure Mode and Effect Analysis (FMEA). The formulation of FMEA intends to describe a system through its components and to separately analyse them in order to identify potential failure modes, their causes, and to assess the potential impacts of these failures in the entire system [Hollenback, 1977].

FMEA approach is especially useful to design a progressive and methodologic process to assess complex systems, in which a similar framework can be repeated through diverse subsystems or components. For FMEA analysis purposes, a failure mode is understood as a deviation from the required performance of a component, i.e., cessation of the ability to perform a critic function. This concept will have specific meanings depending on the semantic characterisations. A basic algorithm for FMEA application [Teng and Ho, 1996] may include:

1. Definition of the system's scope. The division into components and the relationships (utilisations, functions, influences and interconnections) between these components are schematised.
2. Description of each component's function, and their interactions with the others, resorting to block diagrams, for instance.
3. Selection of a primary component.

4. Selection of a function or a performance requirement to be tested.
5. Identification of all the potential failure modes associated with the selected component and function, determining under which operating conditions failure may occur.
6. Selection of a failure mode. Namely one considered as a significant risk.
7. Identification of the root causes of the selected failure mode.
8. Assessment of the direct, intermediate and end effects, tracking a chronological sequence.
9. Identification of the means or methods of detection, as well as existing control and mitigation measures.
10. Planning of supplementary measures and means that may improve or strengthen the element in the context of the selected failure.
11. Selection of a new failure mode. Repeat from point 7.
12. Once all failure modes were analysed, selection of a new function. Repeat from point 5.
13. Once all functions were considered, a new component will be selected. Repeat from point 4.
14. Sorting of potential failures.
15. Proposal of interventions.
16. Registering and documenting the entire FMEA process.
17. Monitoring of the system performance.

This analysis may be especially suitable from the basis of the semantic codification of historical centres and their components. In fact, information such as the description of the component's function, performance conditions and requirements, potential failures and the failure effects, is able to be coded together with the physical entity. In other words, the information needed for carrying the FMEA analysis can be integrated into the models and represented through them. For instance, buildings in which the electric or water supply is critical (e.g., a shelter), or buildings that may be compromised because of inaccessibility (e.g., a hospital).

There are several literature proposals about the risk acceptability in the FMEA method context [Teng and Ho, 1996] , by using qualitative or quantitative indicators. One of the most important aspects to be taken into account is the existence of a societal risk that must be differentiated from individual risks. Societal risks are very sensitive to perception, even if several quantitative measures may be used for an objective approach [Vrijling, 1995]. Several expressions and representations (such as the FN diagram) are useful for contextualising a specific scenario [Stallen et al., 1996]. The results of the FMEA analysis may point out the most critical elements and their most likely failure mode. This critical failure can be further assessed resorting to Failure Tree Analysis and/or Event Tree Analysis.

2.5.3 Fault tree analysis and event tree analysis.

Fault Tree Analysis and Event Tree Analysis are logic trees (i.e., schemes) that represent the different cause-consequence relations existing between different events in the context of the main event. Fault Tree Analysis helps to calculate the probability of failure of a determined system from the analysis of the probabilities of determined disrupting events. On the other hand, the Event Tree Analysis helps to determine the probabilities of a system being able (or not) to cope with a determined disrupting event, taking as a base the chained effects that may be triggered from the main event. Then, both logic trees have in common a determined trigger event. Failure trees explain the events that may lead to the event itself, while event trees describe its consequences for the system. The combination of both trees may be found useful when analysing a very specific event (e.g., a particular earthquake) [Hollenback, 1977, Teng and Ho, 1996]

When addressed to single buildings, the corresponding failure tree may regard the Ultimate Limit State of the structure, based on the different mechanisms of failure for masonry constructions. The event tree analysis may consider the potential effects that a collapse may have in the superior level, due to the presence of debris or loss of continuity in a certain road.

Failure tree analysis helps to assess the events or chains of events that may imply a failure of the system because of the failure of their components. For instance, the city structural breakdown caused by the chained failure of technical networks, housing, business and/or public infrastructures that compromise the basic needs of the city. Time-dependant consequences of that failure can also be assessed resorting to an Event Tree Analysis.

2.6 Towards a comprehensive workflow for vulnerability assessment of HUL.

By departing from the previously analysed information, it is possible to propose a comprehensive critical path divided into four groups of tasks: semantic descriptors selection, semantic description acquisition, modelling and assessment (Figure 2.5). The definition of the semantic descriptors involves the selection of the attributes that need to be coded in order to adequately describe the object in the context of a determined objective. It becomes relevant to select descriptors for the historical centre (streets networks or squares, for example) as well as its components (namely buildings). Since the goal is to carry a vulnerability assessment, it will be necessary to describe all elements that would be used in a Failure Mode and Effect

Analysis. Then, descriptors for the city must express all the use of constructions, infrastructures, networks and entities that permit to have a specific performance (or limit state). On the other hand, descriptors for single buildings should also comprise an elementary characterisation of the structural, material and geometrical characteristics of the building so that a simplified structural assessment can be developed.

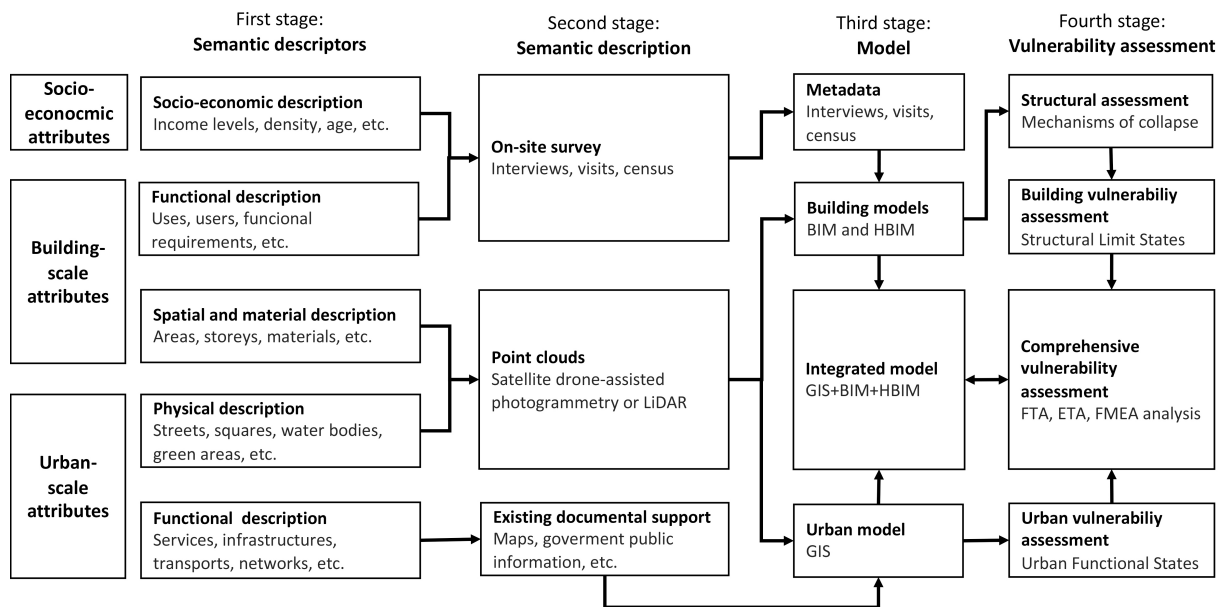


Figure 2.5: Summary of the workflow.

The semantic description refers to the set of measures and characterisations based on the selected descriptors, i.e., the unique description that corresponds to a unique entity. This description is based on an appropriate survey. As reviewed, the selection of the appropriate strategy should be made taking into account, for example, the availability of the resources, the extension of the historical centre and the post-processing capacity. The most current techniques are those of laser scan and photogrammetry, sometimes enhanced with the support of satellite images and/or the use of aerial vehicles. Moreover, this description can be enriched with pre-existing data obtained, for example, from maps or external databases.

The model is the recipient in which the semantic description will be coded, allowing this way to obtain a digital representation of the existing object. Geographic Information Systems and Building Information Modelling are particularly suited to the task of representing historical centres. It is important to keep in mind that interaction between IFC and CityGML standards is still in constant development and implies numerous challenges to be applied in practical projects. Hence, a feasible short-term approach is the simple nesting of BIM models in GIS databases as independent files (i.e., external references), permitting to organise the information that would be able to be more integrated in future.

The vulnerability assessment of historical centres begins by its coding as a system. To do so, it becomes necessary to declare its components (namely buildings, but also streets, services and networks), their interaction and a given performance limit state. For historical centres, this limit state would be a minimum of serviceability when facing an accidental event, such as a fire or an earthquake. In the case of single buildings, it can be related to structural limit states. If a determined event is proposed (e.g., an earthquake with a determined intensity), it becomes possible to assess each building through simplified structural analysis, such as the mechanisms of collapse. When the failure of the individual buildings is inserted in the historical centre Failure Mode and Effect Analysis, we can obtain a determined potential scenario. Suppose the FMEA analysis shows a particular event or the vulnerability of the system (e.g., a bridge). In that case, it is possible to assess a single event of failure through the Failure Tree Analysis and the Event Tree Analysis, so it is possible to study which conditions and situations may lead to the event and the predictable consequences of it.

The proposed workflow shows consistency based on the existence of numerous successful experiences in the literature that cover partial sections of the entire chain. However, a successful comprehensive workflow is still constrained by the numerous challenges found in those experiences as well. The most important technical challenges that were identified during the literature review are related to the automatization of data acquisition from BIM models and three-dimensional point clouds. The simplified vulnerability assessment methodologies discussed in this chapter can be successfully implemented using data that already exists in any BIM model, namely geometrical and material parameters. Then, all attributes might be reunited in a comprehensive survey, that would be able to be filled with data extracted from BIM models as well as from on-site surveys.

The design of adequate interfaces for harmonising both approaches is an important challenge as well. This interface would permit a reliable link between the GIS database and its different sources of information. The representation of BIM and HBIM models in the context of a GIS database is still a very significant challenge, mostly because of the constraints of the computational resources on GIS motors. Nevertheless, this issue has been already explored and is being positively solved through the use of a controlled reduction of details in the Level of Detail framework.

2.7 Final remarks.

The importance of carrying comprehensive vulnerability assessments for historical centres is that of supporting public decisions addressed to the mitigation of the effects that a particular event may impose to

the city. This would help to reduce damages and losses as well as enhancing the recovering capacity after a disastrous event. Existent research has explored how cities and buildings may be analysed and coded in terms of descriptive elements. Some recent technologies are helping to improve the data acquisition processes, also helping to enhance the capacity of obtaining an accurate description of large entities.

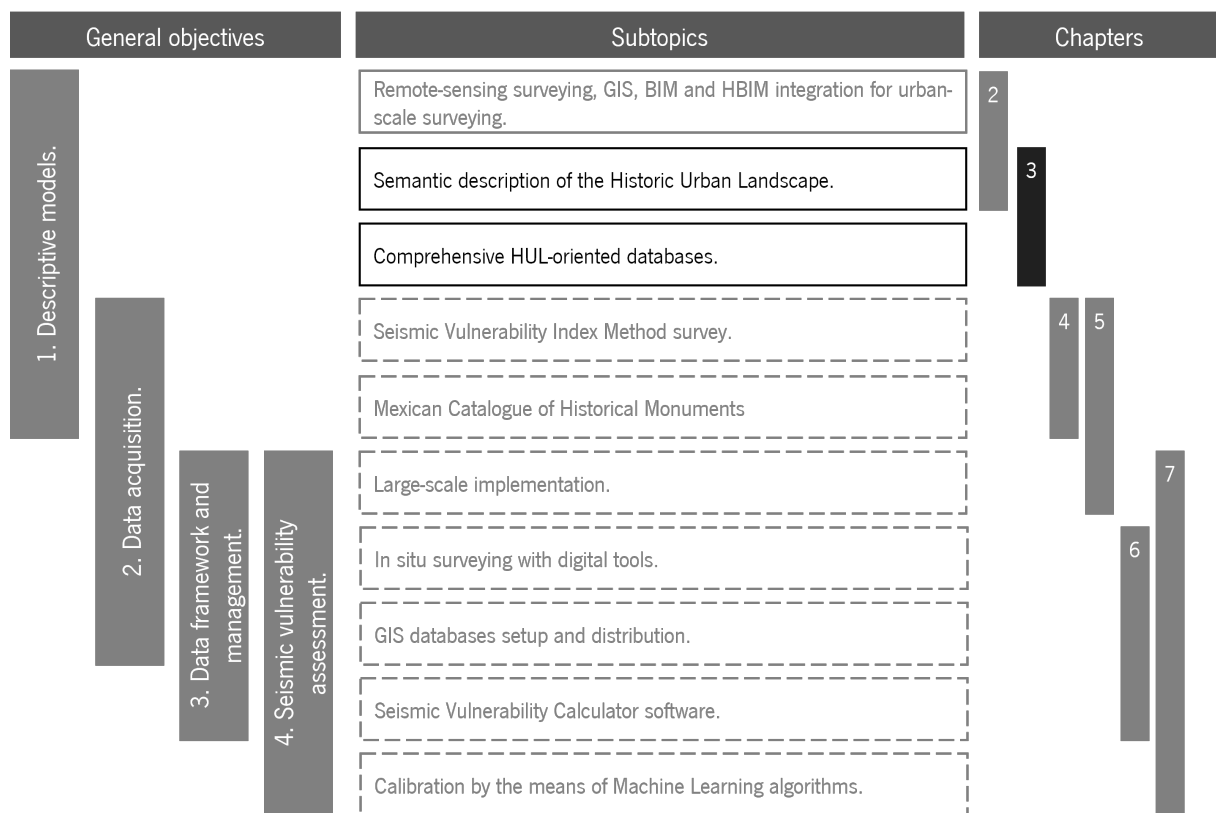
The existing examples found in literature permitted to observe the feasibility of assessing the seismic vulnerability of historical centres through their codification in GIS, BIM and HBIM models. Moreover, this exploration permitted to approximate a workflow in which the semantic descriptors, the survey methods, the digital modelling and the vulnerability assessment share a base and a well-defined sequence. As discussed before, the most relevant challenges of GIS-BIM-HBIM integration are related to the automatization of the data acquisition processes. The current harmonisation of the semantic data stored in the BIM and HBIM models permit to identify the attributes that would be useful to import for vulnerability assessment purposes. However, in order to filter and store the attributes in GIS databases, it becomes necessary to develop proper interfaces, capable of carrying an accurate acquisition from multiple models. When this acquisition is addressed to HBIM models, the existence of multiple approaches for modelling decays and singular elements are still a significant challenge for automatic identification.

The use of third resources such as CityGML would permit to manage the interoperability for models based on the IFC standard for BIM and GIS databases. In this context, the concept and definition of Levels of Detail for models present a significant potential regarding the automatization of the processes and the feeding of the GIS databases from BIM models. GIS databases can be fed with vulnerability-related attributes obtained directly from on-site surveys, but the surveying technologies (such as UAV assisted photogrammetry or satellite images, for example) allow to obtain accurate and large models that facilitate city-scale surveying. Furthermore, the improvements in terms of automatic recognition of surfaces are allowing to achieve the automatic or semi-automatic identification of some elements (namely façades) directly from point clouds. These processes would allow bridging the gap between simplified vulnerability assessment methods and urban-scale surveying.

The literature review allowed to recognise several experiences that represent partial pieces of the proposed workflow. The identification of these successful examples, as well as the analysis of the challenges faced during these processes, allowed assembling a workflow whose suitability is already supported by past experiences where most of the challenges could be successfully solved through the use of state of the art strategies and procedures, namely to automatization and interoperability.

Chapter 3

Comprehensive semantic descriptions for the HUL.



Rafael Ramirez Eudave and Tiago M. Ferreira (2021) *Characterisation of the Historic Urban Landscape through the Aristotelian Four Causes: Towards Comprehensive GIS Databases, Remote Sensing*, 13 (10), 1879. DOI: 10.3390/rs13101879

Abstract.

The Historic Urban Landscape provides a basis to comprehensively study the city, considering the numerous agents and stakeholders involved in the urban phenomenon. However, the characterisation of the city is challenging, due to the numerous ways of reading and using the city. Although several theoretical approaches address the process of documenting the city, there is still a gap related to the design of a generalised, holistic, and comprehensive framework. This article aims to contribute to this purpose by discussing the concept of the Historic Urban Landscape (HUL) and its implications for the characterisation of the urban phenomena. The Aristotelian theory of the causes is proposed here as a suitable approach for the description, characterisation, and analysis of virtually any entity by first discussing its theoretical basis and then testing it in a real building located in the historical city, Guimarães, Portugal. A set of tools related to Geographic Information System databases are comprehensively explored during the implementation process of the approach, allowing to identify and discuss a set of limitations, challenges, and opportunities.

3.1 Introduction.

The documentation of any entity begins by recognising its representative attributes, the convenient code to be used, and how the codification will be conveniently organised and stored. Some codes are commonly given as a matter of fact, due to existing conventions in some fields. For example, to characterise a construction by using plans and photographs. However, it is convenient to recognise that the whole documentation process is meaningful for determining the representativeness of the objects when decoded from the documental source.

As an early-stage step in the process, the survey design and planning have a relevant role in obtaining representative models. These preparatory activities are sometimes underestimated when, for example, a determined set of attributes to be surveyed is given as a standardised model for a determined purpose. It is important to keep in mind that there exist numerous approaches for codifying our physical reality, regardless of the nature of the surveyed object. For instance, a sentence gives a formal characterisation of determined information conveyed by the sentence. If there is a consistent truth condition in the real world, then the sentence can be a reliable sign of reality [Jackendoff, 1976]. In other words, the consistency between the real-world truth condition and the properties claimed by its sign is the key to a proper encoding.

Encode something, then, is closely related to the purpose that the coded representation will have. If the only complete representation of a thing is the thing by itself (law of identity), then any representation necessarily involves a certain loss of information. We can accept that such a loss is neglectable, depending on the purpose or function. Therefore, the convenience and utility of using a determined code represent a problem by itself; if a sign “takes the place” of something, it is critical to recognise during the process of documentation which properties cannot be neglected or lost [Hoskyns, 1934]. This issue is referred to the selection of the characteristics to be documented and the existence of logic and systematic structures for organising data.

This chapter discusses the concept of the Historic Urban Landscape (HUL) and its implications for the characterisation of the urban phenomena. A series of experiences and proposals for documenting the HUL will be presented and used to discuss some challenges and opportunities to comprehensively model the city in the context of its variety and the multiplicity of the actors that converge on it. Then, the Aristotelian theory of the causes will be introduced as a feasible approach for the characterisation and analysis of virtually any entity. This approach will be discussed and put into practice through an example in the city of Guimarães, Portugal. A set of tools related to Geographic Information System databases will be explored, permitting us to identify a set of limitations, challenges and opportunities.

3.2 The Historic Urban Landscape.

The transit on a predominantly globalising and urban world is an opportunity for questioning the role that urban heritage conservation has in the present-day and future urban dynamics. Cities are subjected to numeral pressure sources, such as touristic, demographic, economic, cultural, and infrastructure requirements [García-Hernández et al., 2017]. The growth of the cities is implicitly related to the cultural and economic variety. Most of the changes have been especially fast in the last century, creating a series of generalised and systematic problems that threaten the identity and culture of the communities.

Even if globalisation imposes similarities in terms of financial dynamics, information technology, or urban development among the cities, their culture and heritage are still distinguishable and have unique resources in each one of them. These concerns lead to the design of an interdisciplinary and holistic approach: the Historic Urban Landscape (HUL). This approach pretends to guide the changes of the cities based on the recognition and identification of the natural and cultural, tangible and intangible, international and local values present in any city [UNESCO, 2016].

3.2.1 Definition of the Historic Urban Landscape.

The Historic Urban Landscape is both an approach and a definition: an approach for integrating the urban conservation in a generalised framework for sustainability; and a definition of the historic environment regarding its distinctive elements, identity, and richness [Van Oers, 2007]. The Recommendation on the Historic Urban Landscape [UNESCO, 2011] defines the HUL based on cultural and material traits. It recognises the city as the result of a historical layering of cultural and natural values and attributes, including its surrounding context. If analysed, the definition numbers a series of specific agents to be considered:

«... 8. The historic urban landscape is the urban area understood as the result of a historic layering of cultural and natural values and attributes, extending beyond the notion of “historic centre” or “ensemble” to include the broader urban context and its geographic setting. 9. This wider context includes notably the site’s topography, geomorphology, hydrology and natural features, its built environment, both historic and contemporary, its infrastructures above and below ground, its open spaces and gardens, its land use patterns and spatial organisation, perceptions and visual relationships, as well as all other elements of the urban structure. It also includes social and cultural practices and values, economic processes and the intangible dimensions of heritage as related to diversity and identity.»

This definition is especially meaningful for contextualising the first of the so-called “Six Critical Steps”, which are considered as the minimum steps for implementing the HUL approach: “to undertake comprehensive surveys and mapping of the city’s natural, cultural and human resources” [UNESCO, 2016]. The examples of HUL implementation found in the literature demonstrate that these works of surveying and mapping are difficult to standardise due to the complexity of the HUL-associated phenomena [Rey-Pérez and Pereira Roders, 2020]. The challenge of having comprehensive surveys and maps implies dealing with multiple criteria for selecting significative attributes, having suitable structures and means for data coding and organisation, and designing adequate survey strategies. Besides, it is essential to assess the integration of the HUL in the context of transversal politics, such as the Sustainable Development Goals [Girard et al., 2015, Angrisano et al., 2016], national or local developing plans, etc.

A comprehensive survey may include a wide variety of data, metrics, and indicators. For instance, the categorisation of the promoters and consumers. Landscape and cultural heritage indicators. Or even indicators associated with the performance of the different uses found in the HUL [Gravagnuolo and Girard, 2017]. This condition of the HUL implies the involvement of numerous stakeholders, experts, and professionals with specific interests and scopes towards the historic city. Many of these actors implicitly have specific approaches, namely associated with different ways for modelling and surveying the city. This divergence on the characterisations of the Historic Urban Landscape brings the pertinency of discussing the potential conciliation and integration of multiple interests for a comprehensive characterisation of the HUL.

3.2.2 Experiences facing the challenge of encoding the HUL.

The singularities of the historic city make it challenging to propose universal and standardised approaches. Azpeitia Santander et al. [2018] explore how the development of indicators is still an open debate, referring to some valuable antecedents, such as the ones of the conventions of Vienna and St. Petersburg (Table3.1). Even if there is a categorisation of the city agents, each agent would demand a proper approach for being described. Thus, it becomes important to distinguish if a determined agent is reasonably characterised by its simple categorisation or if it is necessary to provide further descriptions. For instance, depending on the purpose of the description, if it is enough to declare the species of a determined tree for having a series of generic properties, or more detailed information is required to do so.

Another interesting approach for categorising the historic city is provided by Guzman [2020]. This proposal summarises a series of indicators and their corresponding units of measure, based on a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis designed in the context of the sustainable

Cultural–Tangible/Intangible	Economic Tangible/Intangible
Buildings, open spaces, green spaces, public space, designed ensembles, parks and gardens, composition, silhouette (horizontality with movements, views, events, and activities.	Performance in terms of revenues (taxes, tourism, GDP), expenditures (on conservation), relation to the metropolitan/regional economy, marketing potential, and city image.
Social Tangible/intangible	Ecological Tangible/intangible
Accessibility to the city (for living, working, leisure, services) for the population, quality of the housing units, range of housing categories (social housing, middle incomes, high incomes), civic pride.	Biodiversity, water, air, water quality, air quality.

Table 3.1: Key indicators discussed in the 2007 convention of St. Petersburg as referred by Azpeitia Santander et al. [2018].

development of the historic city (Table 3.2). This approach intends to provide a generalised framework for organising a series of indicators that reasonably describe the city. However, since this system is based on the idea of urban performance, it may have some limitations for representing certain types of information, such as geographical parameters. Nevertheless, it represents an interesting approach for pursuing a holistic and comprehensive framework for characterising the city.

Strengths	Weaknesses
Urban size; Protected areas; Green areas or recreational parks; Number of public libraries; Number of theatres and music halls; Festival and religious parties; Number of museums.	Road network; Population density; Literacy rate; Air pollution; Accessibility; Housing; Deterioration phenomena; Marginalisation rate; Community involvement in decision-making processes; Population with access to healthcare.
Opportunities	Threats
Research and development; Financial organisation; Number of police.	Natural risks; Number of automobiles—road traffic; Crime level (robbery).
Conflictive factors	Conflictive factors (cont.)
Number of schools; Number of markets; Productive sectors; Recreational or sport areas; Electricity and light infrastructure; Water supply; Telephone (access, visual disruption);	Investment for intervention; Modes of transport; Access to a sewage system; Population with a university degree; Number of hotels.

Table 3.2: SWOT analysis for the historical city of Queretaro (México). Adapted from Guzman [2020].

The proposal of Kokla et al. [2019] pursues the semantic formalisation of historical centres by interpreting the definition of the HUL, conceiving that the HUL has a complex network of relations with tangible and intangible elements enclosed in an anthropic and natural environment (Figure3.1). Furthermore, the HUL description opens a series of categories that can have individual descriptions and hierarchies depending on the multiple meanings and uses that the historic city has (Figure3.2).

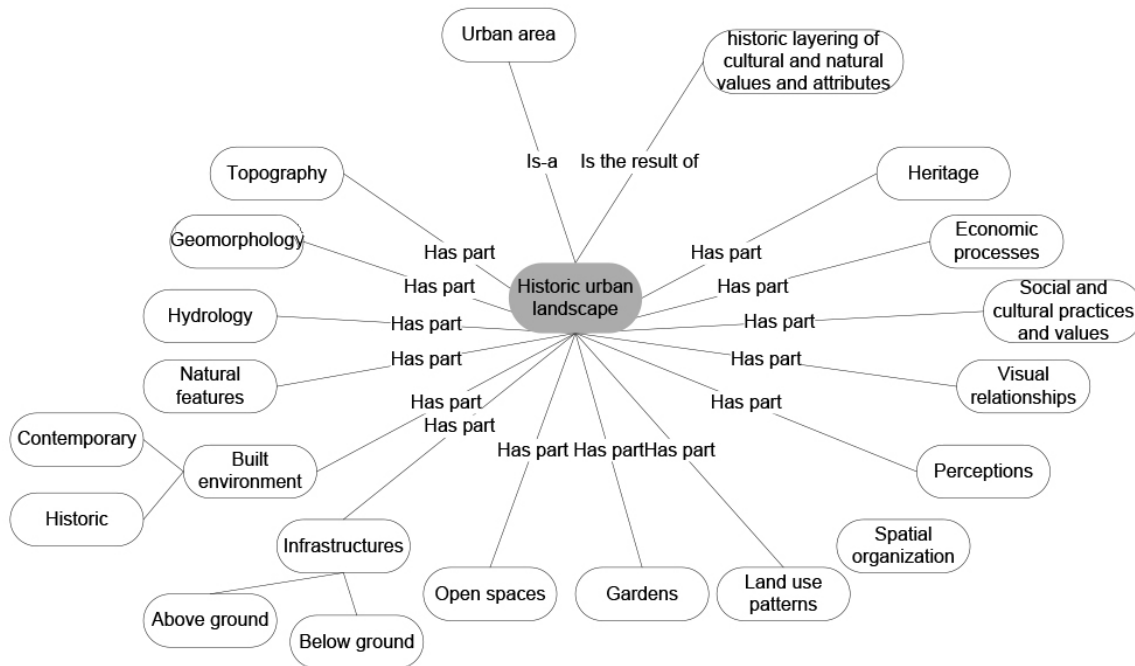


Figure 3.1: Semantic formalisation of “historic towns and urban areas.” Adapted from Kokla et al. [2019].

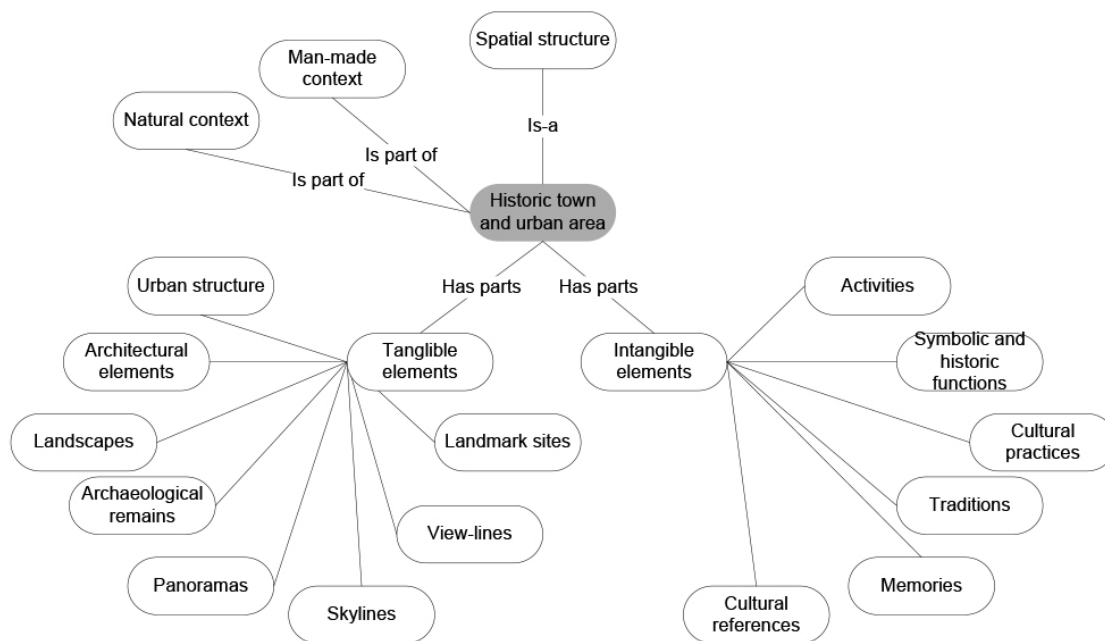


Figure 3.2: Semantic formalisation of the HUL. Adapted from Kokla et al. [2019].

This approach is significant for illustrating a wide sample of fields of interest that converge in the HUL. Furthermore, it is important to recognise that the elements identified in this approach can be further expanded in numerous fields and specialised areas. For instance, the unfolding of the many activities related to cultural heritage. Once again, this schematic representation of the HUL is an approach that suggests the complex challenge of offering a comprehensive description of the city.

The works of Vehbi and Hoşkara [2009] suggest that the identification of representative indicators may result from enquiring a series of causal events and their measurable consequences. For instance, the assessment of the health of a community by measuring the percentage of mothers with adequate prenatal care or the total chronic disease-related deaths per 100,000 habitants. This approach permitted to match the outputs of numerous indicators and the corresponding causing factors for generating a set of sustainable urban revitalisation indicators, divided into economic, environmental, and social indicators. These sets (Table 3.3) are the product of a workflow that includes the parameters' validation.

Many of the attributes considered by these authors share a certain attachment to the building-scale information. In fact, a significant number of urban-scale phenomena can be tracked from information gathered from a building and its permanent or temporary inhabitants. Hence, framing the data acquisition at the scale of a single building would permit the development of numerous surveys with complementary and varied purposes, including the quality of life associated with the cultural heritage [Battis-Schinker et al., 2021].

The review of these precedents reveals that the characterisation of the HUL is still an open and complex discussion that comprises a series of challenges related to the complexity of the city and the actors interested in its study. The design and implementation of generalised frameworks for the comprehensive characterisation of the city are still gaps, whose solution would be a key for the successful implementation of the HUL approach.

3.3 Towards a suitable logic for encoding the HUL.

The characterisation of the current state of the historical city is a critical step towards implementing the HUL approach, which is complementary and interdependent to sustainable urban development. Such characterisation includes a vast number of indicators for modelling the dynamics of a city from the economic, social, cultural, and environmental points of view. Numerous indicators are strongly related to the dynamics between the people and the built environment, such as public services and house facilities.

Economic	Environmental (Physical)	Social
Economy; Ratio of locally/nationally owned business in comparison with national/international business; Unemployment rate Employment diversity (Rate of privately owned business to public business); Local handcraft production rate Income level; Land and property prices (min./max. property prices); Property prices to income level; Rent prices to income level; Tourism; Ratio of tourism facilities in the area; Number and size of recreational; Cultural and spiritual sites; Development costs; Maintenance cost; Land value; Infrastructure;	Environmental quality; Pollution levels: water, air, noise, visual pollution; Energy-transport-Energy-space heating; Transport; Accessibility level (block size-interconnected street, cul-de-sacs, sidewalks); Transportation (Variety of mode of transportation: bicycle, walking, vehicle); Proportion of car parking spaces to build up area; Pedestrian and bicycle-friendly streets; Public transportation; Land (obsolescence indicators—area/building condition); Structural condition of buildings; Proportion of various functions and green spaces; Ratio of built-up areas to open areas (Density of buildings); Ratio of buildings that worth to be preserved; Ratio of incompatible uses; Number/ratio of listed buildings; Rate of historical buildings with adaptive re-use; Proportion of preserved/restored buildings; Rate of the redevelopment of abandoned open space and old areas to the old pattern; Vacancy rate; Percentage of green space in built-up areas; Rate of multi-used buildings; Ratio of solid/voids; Type of public gathering spaces; Rate of use of local construction materials and techniques in new development; Rate and number of public open space with recent intervention.	Income; Income level; Household income disparity Mixed-income; Poor households; Rent-to-income ratio; Crime; Level of safety; Crime ratio; Safety; Health; Sense of well-being; Proportion of population who find their living environment good; Ratio or recreational, leisure activities to the number of inhabitants; Variety of community facilities (educational, health facilities); Existing laws and regulations on urban revitalisation sufficient or insufficient; Accessibility of green space; Availability of local services; Accessibility of local services; Availability of local public open areas and services; Household connection to infrastructure; Number of people using recreation facilities (aware of social and cultural facilities); Household Homeownership rate; Age; Population Cultural/Racial diversity; Civil involvement; Duration in neighbourhood; Housing; Mixed choice of housing; Level of participation in the decision-making process; Floor area per person; Housing price to income ratio Housing tenure types; Housing affordability.

Table 3.3: Sustainable urban revitalisation indicators. Adapted from Vehbi and Hoşkara [2009].

However, the task of reuniting apparently divergent attributes may be problematic when designing a unified scheme for encoding information. Hence, it is pertinent to analyse the step before the selection of the indicators and attributes to be surveyed and discuss how a particular set of characteristics of a physical entity can be organised and enriched regardless of the nature of data and the specific purpose of the model. In other words, it becomes pertinent to discuss purely ontological approaches for generally describe and analyse entities, departing from an unbiased interest.

3.3.1 The Aristotelian Causes as an approach for categorising the surveys.

The accuracy of the description of an entity is necessarily dependent on the formulated questions. In this sense, the singularities of the cities (and their components) make it challenging to establish a standardised framework. Nevertheless, as discussed before, several authors agree on studying the impact that singular agents have in the historic city's context from the economic, social, cultural, and environmental points of view. To systematise the data acquisition for understanding each one of these dimensions is not necessarily a single work but the sum of numerous sets of suitable and specific surveys. However, the discussion is still open, and there are several intents for proposing robust frameworks for formalising and organising the sets of characteristics that define the HUL and its elements.

A plausible approach for categorising the layers of information to be surveyed from an entity can be understanding it through the Aristotelian principle of the four causes. This approach fundamentally accepts that there are four elemental answers to the question “why?” when analysing an entity: the material, formal, efficient, and final causes. This theory frames any entity in a hypothetical continuum of causes in which each one of the elements that compose a determined entity has its own sets of elemental causes [Gómez-lobo, 1996].

Generally speaking, the material cause regards the tangible matter that represents the object in the physical world. The formal cause is the arrangement, organisation shape, appearance, or spatial consequence of the entity. The efficient cause is the set of external agents whose intervention permits the existence and performance of the object [Heidegger, 1977]. The final cause is the purpose and/or function that an object has [Hocutt, 1974].

It is relatively easy to recognise these elemental components in simple and paradigmatic objects, but a more complex analysis may make it difficult to categorise the causes in a precise manner. A classic example consists of analysing a table. In this case, the material cause may be wood, metal, plastic, or any other material. The formal cause will be the geometrical description of the table. The efficient cause would be the carpenters that fabricated the table. A final cause for the table would be to eat on it, for

example. The assessment of a building is not that simplistic, of course. However, the categorisation of some sets of attributes would help organise the information. Furthermore, a nested organisation of the layers of information would permit the design of a unified framework.

The interest of analysing entities by using this approach lies in the possibility of establishing a unified logic for successively exploring the parts of an entity until the level of information detail is considered satisfactory for a determined purpose. For example, we can declare that the material cause of a building is “masonry.” This answer may be satisfactory enough for a specific purpose, such as cataloguing, but insufficient for obtaining relevant information about the structure. Hence, it would become relevant to explore the causes of the “masonry”, i.e., the exact attributes that specifically belong to “that” masonry.

This nested and enlargeable structure permits categorising the fundamental causes of an entity regarding the four different types of causes, being that a cause can be related to an unlimited number of instances able to be further analysed. It is possible to individually describe these instances or categories by categorising their own causes. The process of categorisation and description has a certain fractal development, in which it is possible to explore diverse elements of an entity with different levels of deepness without losing consistency. An example of this procedure is depicted in (Figure 3.3), where a plausible structure for finding a causal link between the HUL and the mortar of a determined building.

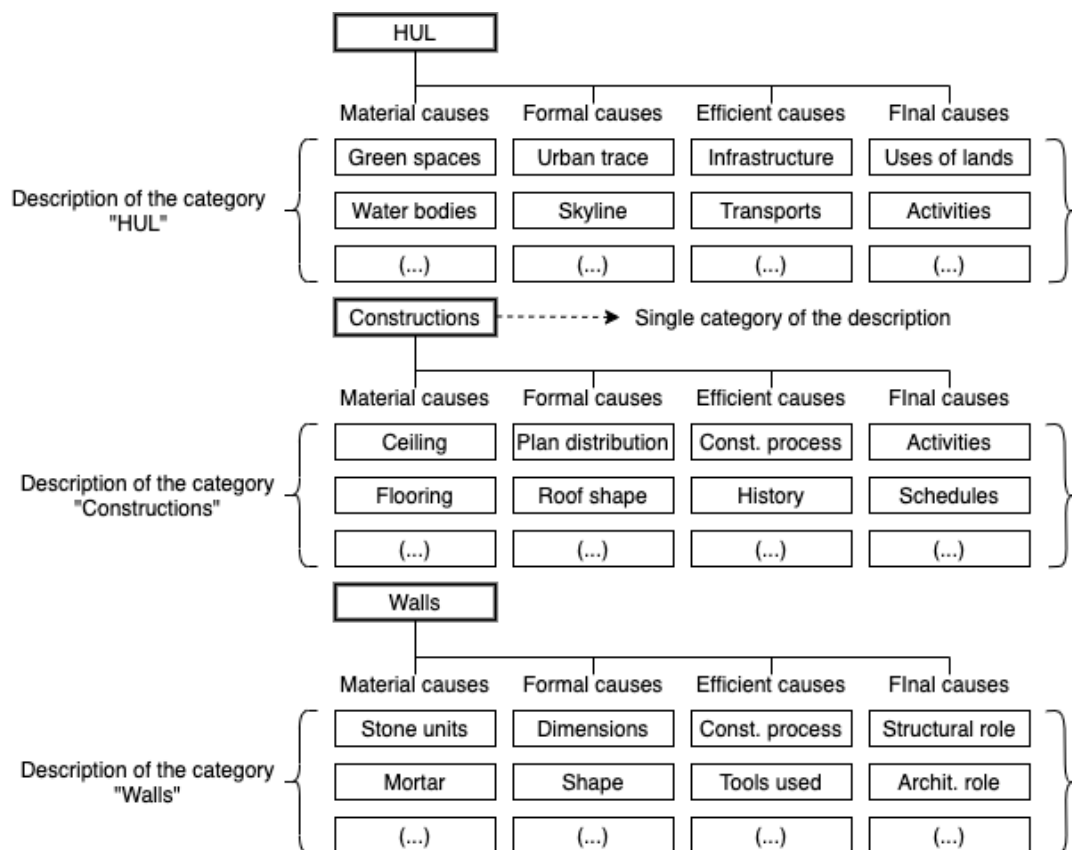


Figure 3.3: Example of a nested analysis of causes.

When analysed from its fundamental causes, the HUL may have a series of instances. For example, the material causes of the HUL (i.e., the tangible components of the HUL) may be itemised as a series of generic instances, such as green areas, water bodies, and buildings. Naturally, each instance can be further analysed and categorised. In this example, there is interest in unfolding the causes for the constructions, and consequently, a series of instances is proposed according to each fundamental cause of them. It is worth noting that this categorisation can be as exhaustive as necessary, framing more specific instances, such as “houses” instead of “buildings”.

The analysis of the material causes of a building proposes a series of instances that determine the materiality of the construction. The process of determining these instances has been extensively explored in the past, namely in the context of the Building Information Modelling approaches. In fact, the standardisation of components and libraries (namely based on the IFC standards) offers a robust point of departure [European Commission, 2017]. Finally, when exploring the material causes of a wall, it is relevant to find a suitable position for establishing the instance of “mortar” and its further analysis.

The causal analysis, however, can be supported by some generalising ideas. For a building, the material causes would be all the substances that give tangibility to the construction. The formal cause would be the spatial consequences of the building: its geometry, shapes, volumetrics. The efficient cause is the set of agents that possibilities the existence of the building. However, in a broad sense, it is not only who built it and how, but what does permit to keep the building’s ontological efficiency and/or performance. For instance, a house without a water supply is not properly working according to the “house concept”. It is important to recognise that the efficient cause is closely related to the expected performance of the entity. In other words, it is closely associated with the final cause, which represents the use of the building, its users, and its dynamics of use.

To feasibly generate a flexible approach based on the Aristotelian principles, it is necessary to design and manage databases able to be enlarged as much as necessary, permitting to store and manage qualitative and quantitative data without losing the structured organisation. The control of the granulometry of the information for representing the built environment has already been explored for representation purposes in digital models. Approaches, such as the Level-Of-Detail for three-dimensional modelling, propose generalised frameworks for defining thresholds for the information contained in a model [Ramírez Eudave and Ferreira, 2021b]. However, this approach does not observe the flexibility for selectively having different levels of detail in multiple instances of the same model [Biljecki, 2017]. This customised compartmentalisation of the information is expected to satisfy the need of the various stakeholders of the HUL for an accumulative, multidisciplinary, and coherent framework.

While most of the examples found in literature build on a tree-structured organisation of the information, the Aristotelian approach is closer to a fractal development. Since the steps between instances are self-similar (i.e., based on the same set of four causes), the structure of successive steps (regarding the detail or granulometry of information) may be understood as a progressive unfolding of causes in different scales.

A very representative schematization of this recursive process may be found in the so-called “Cantor dust”. This fractal progression departs from a square that is subsequently divided into four subsets. Suppose we admit that each step corresponds to the fragmentation of an instance in its four fundamental causes. In that case, it is possible to see that the structure represents the progressive nature of this analysis.

Furthermore, from this geometrical schematization, one can observe that the process of fitting the descriptors needed by multiple stakeholders in this structure allows assembling a coherent and comprehensive description in upper levels. As shown in Figure 3.4, different stakeholders would need to analyse diverse aspects of the entity with varying levels of granulometry of data. For example, a determined stakeholder may be interested in knowing if a specific construction is made of masonry, whereas another stakeholder would need to specifically know which kind of stone is that masonry made of (Fig.3.5). Thus, if clearly structured and organised, the information generated by a stakeholder can be potentially valuable as a full integrative description.

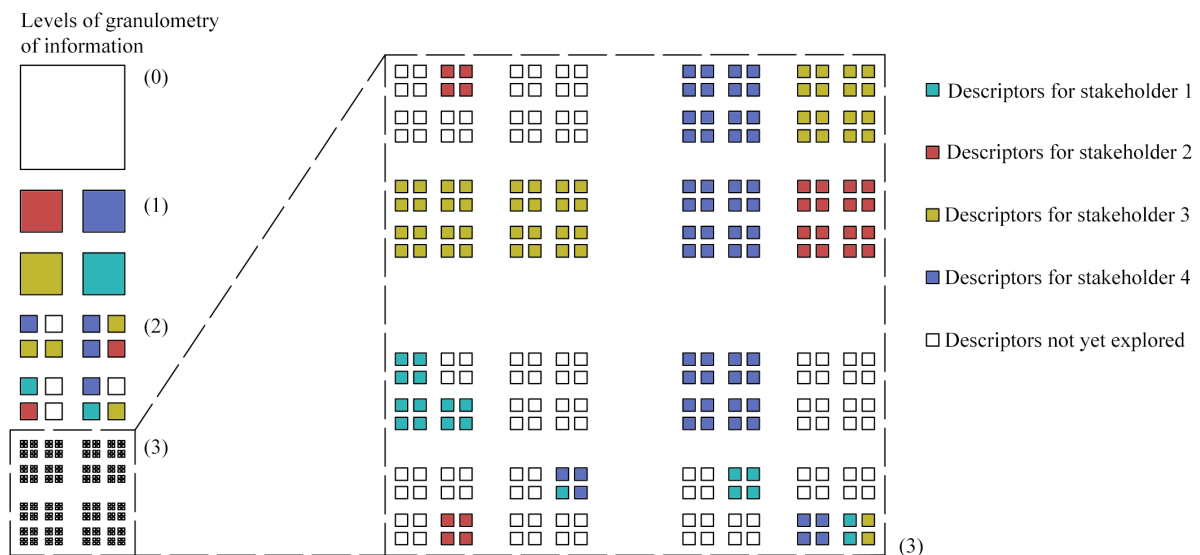


Figure 3.4: The “Cantor Dust” fractal as a schematic representation of the proposed approach. The level of specificity or granulometry of information is here schematized by departing from the more general level of information (0) and subsequent stages of more detailed analysis (1), (2) and (3).

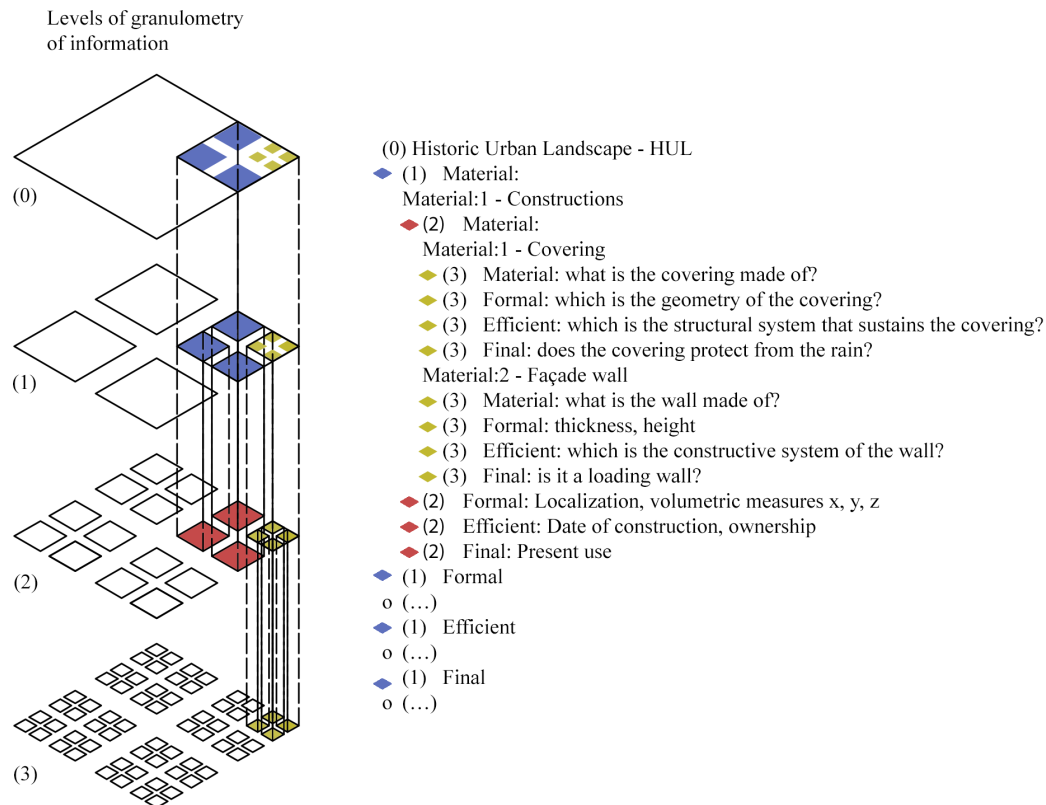


Figure 3.5: Schematization of a series of attributes fitted in an HUL structure.

It is worth highlighting that, even when different stakeholders develop independent surveys with specific queries, provided that similar criteria are used for organising the levels of information and the relations among the elements of the HUL, a collaborative database can be eventually obtained, as shown in Fig.3.6. This figure also illustrates how a single stakeholder would be interested in information with different levels of granulometry without compromising the uniformity and order of the structure.

This approach is particularly meaningful when used for structuring databases—ideally integrated with existing tools and survey methods, for ease's sake—to be fed, consulted, and managed by multiple stakeholders. Just as different stakeholders converge in the HUL, there is a wide set of databases and platforms for managing HUL-related data. One of the most versatile, well-known, and diffused ones are the Geographic Information Systems (GIS).

3.3.2 The Use of a Geographic Information System-based workflow for facilitating on-site surveying.

Since its emergence, Geographic Information System platforms have been valuable tools for organising and managing information related to the physical world. Nowadays, due to the accessibility to free and open-

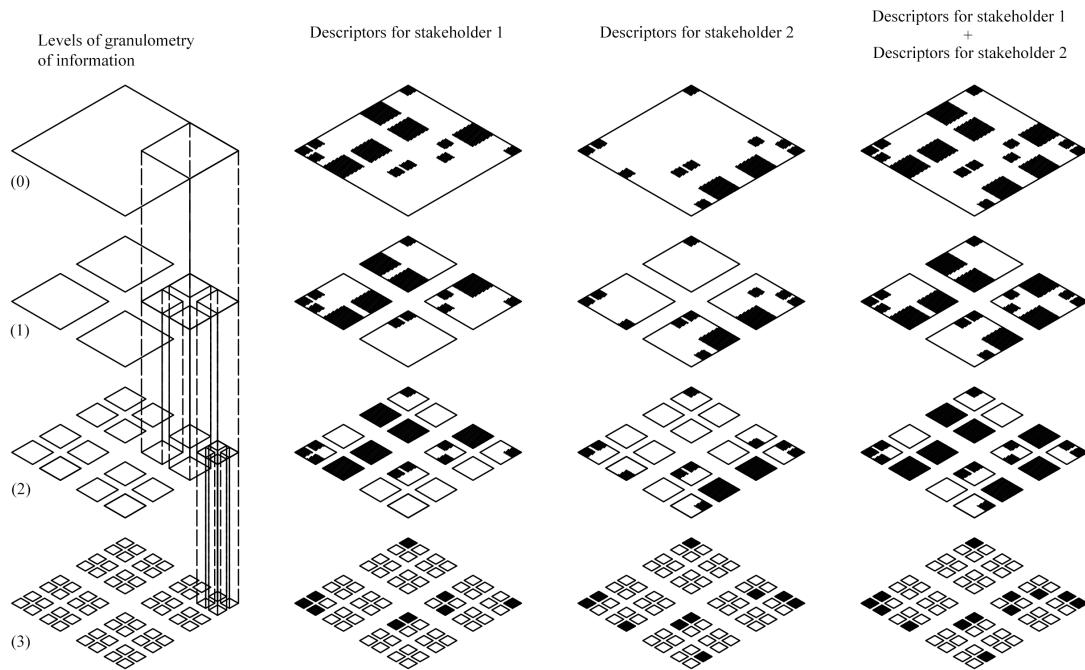


Figure 3.6: Schematization of the convergence of different surveys in a unified model. The level of specificity or granulometry of information is here schematized by departing from the more general level of information (0) and subsequent stages of more detailed analysis (1), (2) and (3).

source software, GIS tools are available for a vast number of stakeholders with interests in the territory and the environment. GIS databases offer information from various sources, including thematic maps developed by governments, research institutions, and specialised agencies [Eastman, 2005].

An interesting possibility of the use of GIS is to facilitate collaborative work for assembling databases. In fact, there are numerous tools and software that permit sharing a GIS database between multiple actors [Skilodimou et al., 2019]. This implicit advantage is compatible with an approach based on the selective enlargement of the database. For instance, it is possible to design a public semantic structure for categorising the levels of information. Each category would be associated with its proper set of descriptors according to the four causes. At the same time, each descriptor can become a category for further descriptions, if needed. Then, the structure would be systematically enlarged based on a primary and controlled structure.

The strategies for data acquisition must be compatible and coherent with the nature of the surveyed information. As analysed before, a significant part of the meaningful attributes of the HUL depends on the information of different scales. Therefore, it becomes relevant to suggest an adaptative, economic, and suitable survey strategy to be used by different users and stakeholders.

A feasible approach for the collaborative work on GIS databases is to store the database file in a cloud service that numerous (preferably portable) devices can simultaneously access. If those devices permit

the edition and real-time synchronisation of the file, it is possible to sustain a dynamic database in constant change and enrichment. This goal, however, is much more feasible when using open-source and/or free distribution software. The integration of the QGIS + Mergin + Input software is an extraordinary example of the possibilities offered by a GIS cloud-based distribution interacting with open-source software.

QGIS is an open-code and multi-platform Geographic Information System, supported mainly by the voluntary contributions of code, corrections, and collective support. This interdisciplinary enrichment favoured the design of a comprehensive set of plugins and extensions for multiple purposes, even integrating third-party tools and software. Mergin, one of these extensions, allows store files developed in QGIS in an ad-hoc cloud. One of the products associated with Mergin is Input App, an application developed for smartphones and other portable devices. Input App allows to access, manage, and synchronise the files stored in the cloud. Therefore, these three tools constitute a closed and bidirectional workflow, see Fig.3.7. The files stored on Mergin can be either public or private, permitting to decide between generalised access (to anyone with the app) or a limited one, i.e., through invitation.

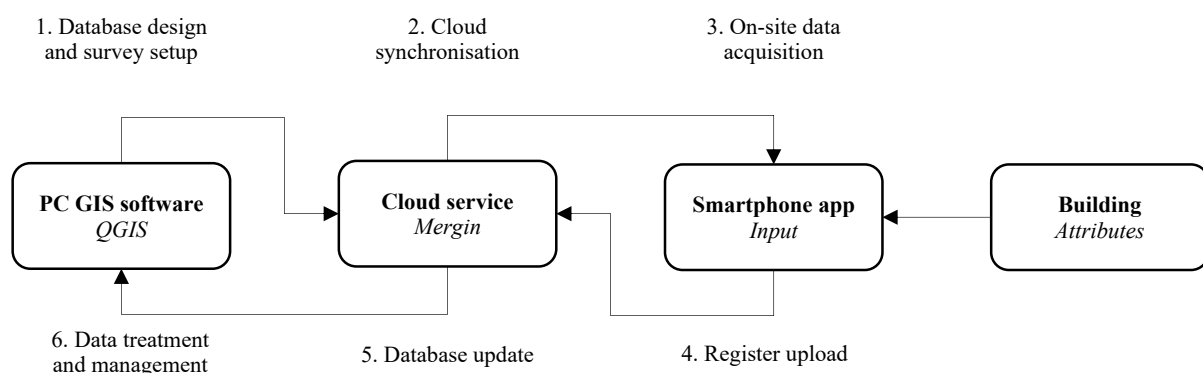


Figure 3.7: Flow schematization for the integration QGIS-Mergin-Input App. Adapted from Ramírez Eudave and Ferreira [2021a].

In fact, there is a wide set of public projects that reveal the collaborative potential of this tool. Some specific experiences have explored the potential of programming a customised survey for a specific purpose—for example, Ramírez Eudave and Ferreira [2021a] have implemented a seismic vulnerability assessment-oriented survey to be used in field survey campaigns.

Since Input App takes advantage of the mobile devices' GPS service, the information can be stored with an inherent georeferentiation. This characteristic is significant when mapping or surveying the elements of the HUL. The field survey accessed through Input App depends on the queries programmed in the QGIS platform and the constraints imposed in the database. QGIS and Input accept multiple types of variables, including attached files such as photographs.

3.4 Worked example of application.

A short workflow has been put into practice in the following to illustrate the ideas explored in the previous sections. As discussed in the previous sections, the success and representativeness of the models depend on the use that the model will have. In this context, the exercise is framed in the context of the characterisation of a historic building for seismic vulnerability assessment purposes.

The entire workflow will be applied to the ancient church of São Miguel do Castelo (Fig.3.8). This historic building is part of the set of monuments of the city of Guimarães, Portugal, recognised as World Heritage by UNESCO (2001).



Figure 3.8: Church of São Miguel, Guimarães, Portugal: main façade (a) and nave view (b).

3.4.1 Workflow design and considerations.

This process will begin with the description of the attributes (instances) considered relevant in what the characterisation of the seismic behaviour of the building is regarded. Those attributes will be framed in a potential structure for the HUL of the city of Guimarães, considering the causal structures in which the instances will be located. This part of the example will present the suitability of a determined set of descriptors in the context of an Aristotelian causes-based description. The following considerations were taken to make this example as illustrative and realistic as possible:

- The constructions are here framed as one of the material causes of the HUL, understanding a primary division on natural and anthropic elements. Since this example is focused on describing

a building, no further analysis will be proposed on the rest of the fundamental causes of the HUL. These causes, however, can always be explored whenever necessary. In fact, the unfolding of causes is, as discussed before, a virtually endless activity.

- The Aristotelian causes are a guide for coherently orient a series of questions regarding the materiality, geometry, performance, and function of something. Then, it is possible to have a set of queries for satisfying the explanation of a cause more than a single attribute or field. For instance, one of the many purposes that a masonry wall may have is to be seen with no plaster. This has an architectonic purpose as many different purposes that a determined masonry may have. The interests of different stakeholders may enrich the final cause of the masonry if needed.
- The material cause of a building is primarily considered in basic elements: covering, flooring systems, and façade. Each one of them can be further expanded if needed. This example considers that special attention is paid if the construction has masonry walls as external vertical structures.
- The formal cause is addressed to the localisation and the building's volumetric measures—since both are spatial constraints.
- The efficient cause may include who built the construction and the means used for its erection. This information is not considered for this example but can be meaningful for other specific purposes. Besides, the users are considered as an efficient cause since their action sustains the activity that the building is supposed to have. The information about the users is also able to be further expanded if needed.
- It helps think in terms of categories instead of descriptions when the fundamental causes do not seem to make sense in a determined context. For instance, it may be illogical to question the matter of a user, but it would make sense if a determined construction is a greenhouse, and its efficient cause is closely related to vegetal individuals.
- The efficient causes represent the circumstances related to the creation of the building and the sustenance of its performance conditions. Hence, a part of the system's performance is its conservation state. Even if it is not explored in this example, the availability of electricity, water, and sewage may be explored if needed.
- The final use may involve agents, such as the explanation of the economic activities, the assets that the building houses (proper when addressing museums, collections, or stocks), the specific conditions for operability, etc.
- The tree is not exhaustive but exemplifies how a determined specific interest can be introduced in a structure that can be further expanded for storing information valuable for numerous actors.

3.4.2 Parameters and queries.

The seismic vulnerability assessment approach adopted herein is based on the evaluation of fourteen parameters related to the seismic performance of the building's façade wall [Aguado, 2017]. Each parameter receives one of four potential grades (A, B, C, and D) based on specific qualitative or quantitative conditions. Given the set of 13 characteristics to be evaluated, a set of 43 queries was defined:

- FP1. Geometry of Façade
 - Q1. Length (B) in m
 - Q2. Height (H) in m
- FP2. Maximum slenderness of the façade
 - Q2. Height (H) in m
 - Q3. Thickness (s) in m
- FP3. Area of openings
 - Q4. Ratio opening/solid wall (%)
- FP4. Misalignment of openings
 - Q5. Have all the openings a regular size? [Y; N]
 - Q6. Are the openings aligned in height? [Y; N]
 - Q7. Horizontal misalignment in more than 1/2 of height [Y; N]
 - Q8. Vertical misalignment in more than 1/2 of height? [Y; N]
 - Q9. Large opening at the ground floor level?
- FP5. Interaction between façades
 - Q10. Left adjacency: [none; shorter; same height; taller]
 - Q11. Right adjacency: [none; shorter; same height; taller]
- FP4. Misalignment of openings
 - Q12. Units of masonry: [brick; stone; mixed]
 - Q13. Type of brick: [solid; > 45% voids; < 45% voids]
 - Q14. Quality of execution: [good; regular; poor]
 - Q15. Laying and connection irregularities [Y; N]
 - Q16. For stone: [well carved; irregular; unworked units]
 - Q17. Unworked units of heterogeneous dimensions [Y; N]

- Q18. Presence of voids [Y; N]
- Q19. Transversal connection between layers [Y; N]
- Q20. Presence of visible cracks [Y; N]
- Q21. Depth of cracks: coating or structural [None; coating; structure]
- Q22. Signs of repaired cracks [Y; N]
- Q23. Cracks due to deformation and/or settlements [Y; N]
- Q24. Bending and oblique cracks [Y; N]
- FP8. Replacement of the floor system
 - Q25. Ratio of concrete floor systems/total of flooring systems (%)
- FP9. Connection to orthogonal walls
 - Q26. Metallic strapping elements, tie rods [Y; N]
 - Q27. Good laying and locking of masonry [Y; N]
 - Q28. Deformations, disconnections, detachment, or embrittlement
- FP10. Connection to orthogonal walls
 - Q29. Ratio of diaphragms efficiently connected to the façade (%)
 - Q30. Signs of deformation, rotting or retraction [Y; N]
 - Q31. Signs of fragility in the support zone [Y; N]
 - Q32. Signs of distortion [Y; N]
 - Q33. Lack of circulation safety [Y; N]
- FP11. Impulsive nature of the roofing system
 - Q34. Span (m)
 - Q35. Height (m)
 - Q36. Symmetric or asymmetric [Symmetric; Asymmetric]
 - Q37. Thrust-cancellation elements [Y; N]
 - Q37. Strapping reinforce perimeter [Y; N]
 - Q38. Conservation status [bad; regular; good]
 - Q39. Strapping reinforced perimeter or tie rods [Y; N]
- FP12. Elements connected to the façade
 - Q40. [none; light (light, signs); medium weight (equipment, AC); heavy (balconies, parapets)]
- FP13. Improving elements

- Q41. Exterior stairs, arches, giants, etc. [Y; N]
- Q42. Strengthening actions [Y; N]
- Q43. Presence of reinforced plasters (e.g., with meshes) [Y; N]

The grading for each parameter depends on a series of qualitative or qualitative attributes. Hence, a parameter is, in fact, the result of a series of basic conditions. Thus, it is necessary to establish a list of individual attributes that comprise all the information needed for categorising the parameters. The queries will be then set in the corresponding attributes table of the GIS database so that they can be individually obtained during a field campaign.

As discussed in the previous section, each individual query can be framed in a specific section of the causal HUL schematization, which translates into the relationship between the attribute, indicator, or metric and the other elements of the building and the HUL. Then, it is necessary to consider the specificity of each query in the context of the deconstruction of the HUL in successive causal instances.

The queries present a variety of types and potential answers. For example, there is a series of queries where the answer is meant to confirm or deny a specific aspect (e.g., if all the openings have a regular size). Some others need the introduction of quantitative information, such as the height and length of the façade, or imply the selection of a condition from a closed set of options. All these non-numerical queries can be determined in the QGIS software under the scheme of a map of values, which permits further data treatment.

3.5 Results.

3.5.1 Fitting of the instances in the causal structure of the HUL.

It is worth recognising that the organisation of the parameters and queries of the Vulnerability Index Method are not comparable because the queries correspond to different instances and levels of granulometry. This independent development is expected to occur for almost any set of attributes and/or customised survey. On the other hand, the organisation based in the HUL causal structure is expected to permit the localisation of virtually any potential attribute, metric, or query used to describe the elements of the HUL.

The organisation of the queries in the HUL scheme (Fig.3.9) unfolds from the HUL itself, at the top of the structure. It is possible to identify a series of intermediate steps that may have been considered between the HUL and the buildings.

For this exercise, buildings are considered as one of the material causes of the HUL. It is possible to find that the material causes of the HUL are even more general, such as an initial categorisation between natural and artificial objects. Since the structure is expandable without losing the order and hierarchies of the granulometry, this is not considered an issue nor a limitation but a potential part of an enlarging process.

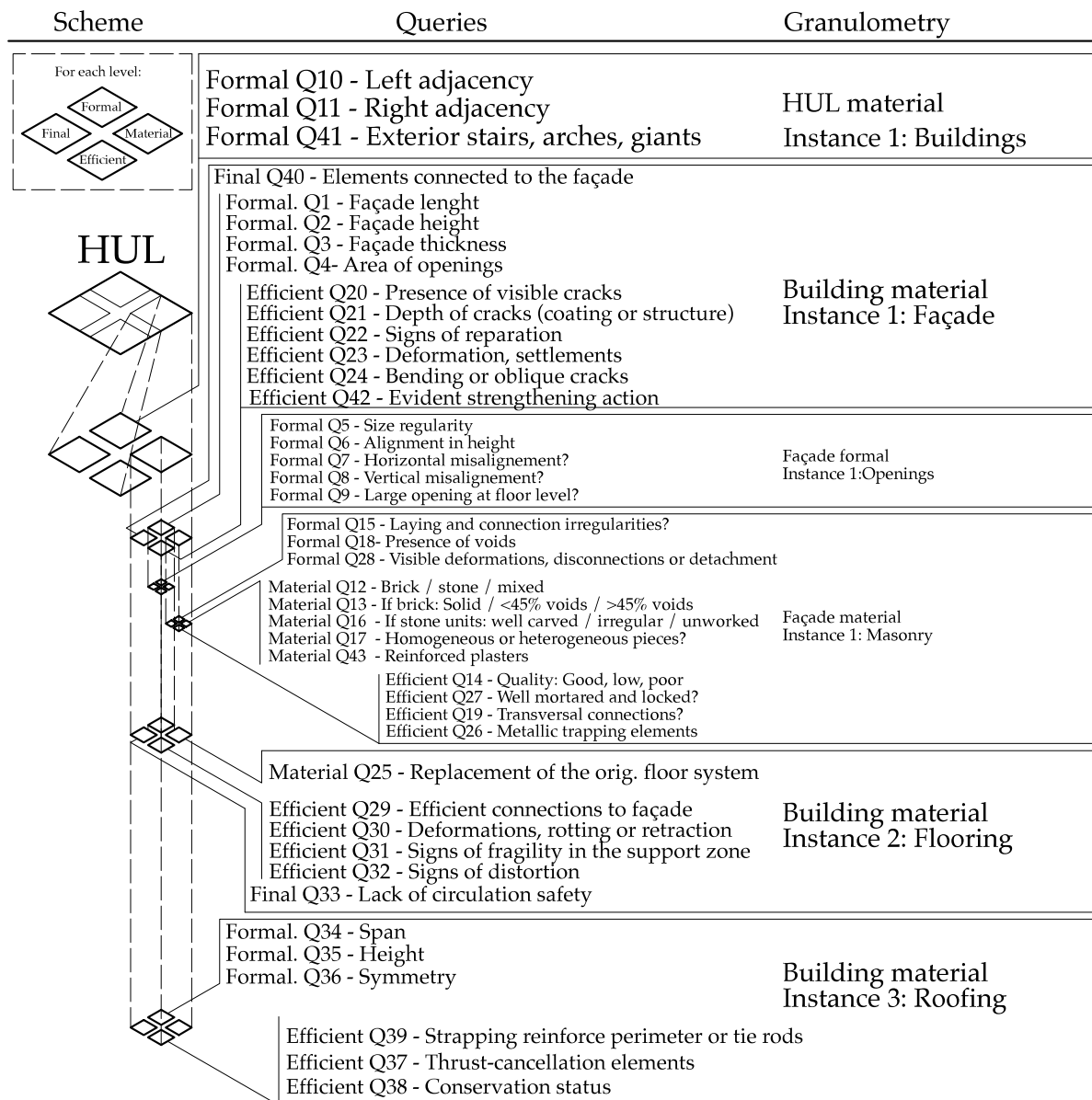


Figure 3.9: Schematization of the HUL structure by using the Cantor Dust fractal representation, the correspondence with the queries, and the descriptive stages of granulometry of the information.

The analysis of the building allows for a first approach to the most general queries, those related to the exterior geometry and spatial description of the building and its adjacencies. It is interesting to note that this organisation and the level of granulometry has a logic development that is similar to the Level-of-Detail approach, suggesting a potential convergence in future analysis.

As a material instance of the HUL, buildings are subsequently analysed in their four fundamental causes for finding the next level of information. Most of the queries for the parameters are related to the structure of the building. The material causes of the building were unfolded in three instances (that would be more for a different analysis): façade, flooring, and roofing system. These instances are primarily considered as material causes since they represent general parts of the tangible substance of the construction. The analysis of the first instance—the façade—, permits us to answer some more specific queries. A very illustrative query is Q40, which relates to the existence of elements connected to the façade. From the point of view of those elements, the façade is the support, and, in consequence, it is analysed from the final cause. The formal causes of the façade permit the extraction of metrics related to its dimensions, whereas the efficient causes permit to inquiry about the damages and pathologies that condition the structural performance of the façade.

It is important to note that the analysis of the attributes of the masonry is conveniently divided into a subsequent level. The formal cause of the façade is unfolded in the first instance: the openings. Even if this unfolded instance is only analysed from its formal causes (namely the size, organisation, and alignment of the openings), it can be used in the future to include additional information with a different purpose.

Just as for the formal cause of the façade, the material cause has been unfolded in a first instance, that of masonry. It is important to note that this approach is for masonry façades only, but the causal analysis does not exclude the possibility of unfolding several material-related instances. The causal analysis of the masonry permit to summarise its geometrical configuration and potential deformations (formal causes), the type of units used (material causes) and its construction system, quality, and status (efficient causes).

The second instance of the building's material cause—the flooring system—is analysed from its material, final cause, and efficient cause. The analysis of the efficient cause of the flooring illustrates how a series of conditions related to pathologies and decays of an element is an integral part of its efficiency. Finally, the third instance for the building's material cause—the roofing system—is described in terms of geometry (formal causes) and construction elements that permit its performance as covering (efficient causes).

When articulated together, the scheme and the queries illustrate a process of selection and organisation for attributes that can be replicated for different and variate purposes, though permitting the assembling of a comprehensive and complementary database. The instances and levels analysed for this example are only a first approach that would be enlarged as needed according to the requirements of other analysis and agents.

3.5.2 GIS database setup.

The church of São Miguel was selected and tagged based on an existing GIS database of the historical city of Guimarães. It was possible to draw a preliminary polygon resorting to the Open Street Maps public database as a primary source. The base map was created in QGIS (Version 3.12 Bucuresti). The representative polygons of the buildings were isolated in an independent layer, in which the queries were encoded in the corresponding attribute table (Fig.3.10). When programming the queries, it is essential to distinguish the type of variables to be encoded: those that correspond to real numbers (such as measurable properties), the logic true/false fields, and the multiple value ones.

Q1_Façade lenght	0,01m
Q2_Façade height	0,01m
Q3_Façade thickness	0,01m
Q4_Area of openings	0,01%
Q5_Size regularity of openings	☐
Q6_Openings aligned in height	☐
Q7_Horizontal misalignment in more than 1/2 height of opening	☐
Q8_Vertical misalignment in more than 1/2 of height	☐
Q9_Large opening at floor level	☐
Q10_Left adjacency height	
Q11_Right adjacency height	
Q12_Units of masonry	
Q13_Type of brick	
Q14_Quality of execution	
Q15_Laying and connection irregularities	☐
Q16_Stone units	
Q17_Stone: unworked units of heterogeneous dimensions	☐
Q18_Presence of voids	☐
Q19_Transversal connection between layers	☐
Q20_Presence of visible cracks	☐

Figure 3.10: Screenshot of the attribute table and the empty fields to be obtained.

Once the 43 queries were adequately encoded, the project was synchronised in the Mergin cloud storage service. It is important to remark that the present-day free hosting service is limited to 100 MB, which can limit the inclusion of attached files (namely photographs) as part of the survey. This issue, however, is not relevant in the context of this example. It is also worth noting that this workflow uses only one of the potential open-source-based software sets and does not exclude similar strategies with other tools.

3.5.3 Data acquisition.

When in the server, the project can be then downloaded and consulted locally using the app Input (version 0.9.2) on any mobile equipment running an Android or iOS system. This app allows to access the QGIS project and to capture the data gathered on-site by fulfilling the queries proposed for the attribute table. Since the app permits a real-time position in the georeferenced map, the constructions can be identified easily (Fig.3.11).

The information gathered through the Input interface was synchronised with the cloud service, allowing its storage, consult, and managing within the QGIS interface (Fig.3.12). Besides, the QGIS software possibilities to export the data in various formats, facilitating further analysis and use for different stakeholders, namely for carrying external processes. The GIS database offers, in fact, the possibility of executing relatively simple operations fed by the data in the attribute table, but it may be limited for certain purposes.

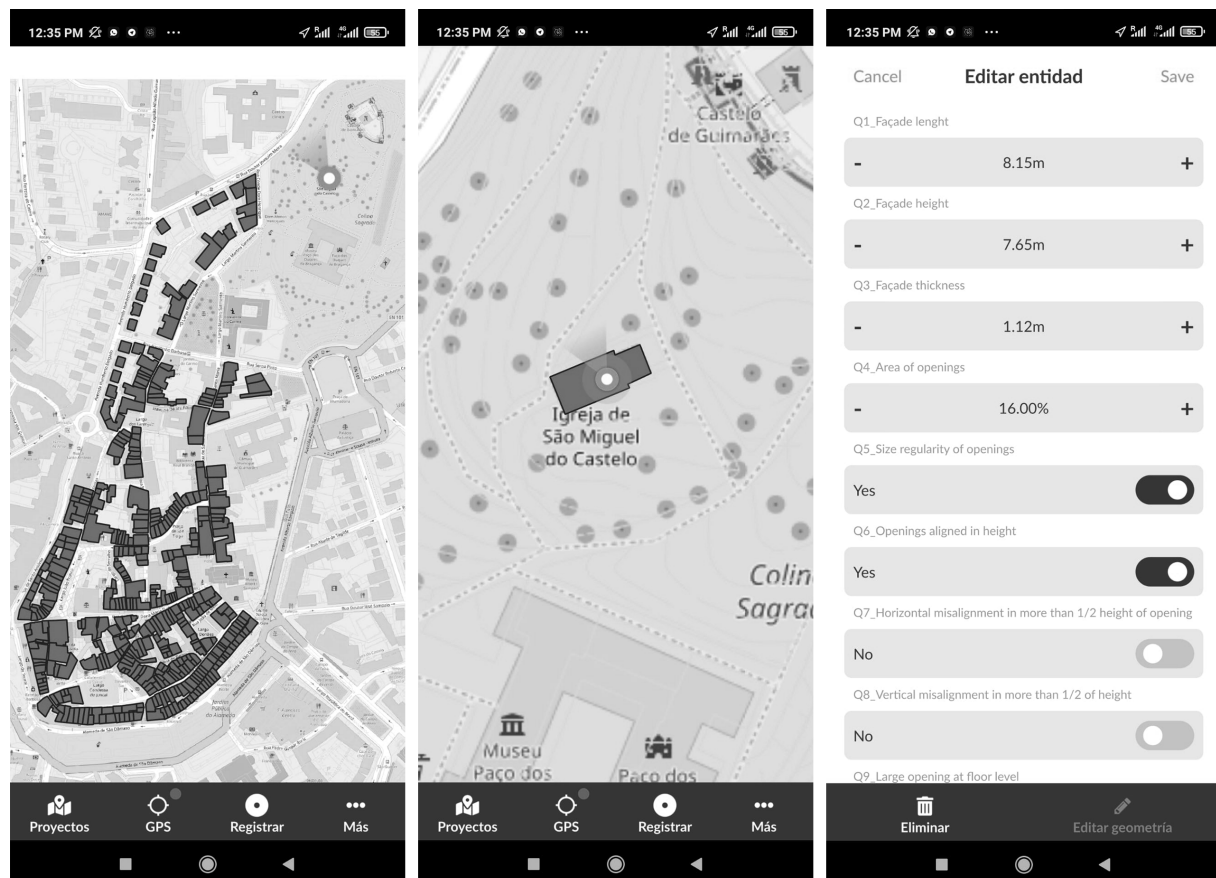


Figure 3.11: Screenshots of the app Input during the on-site survey work.

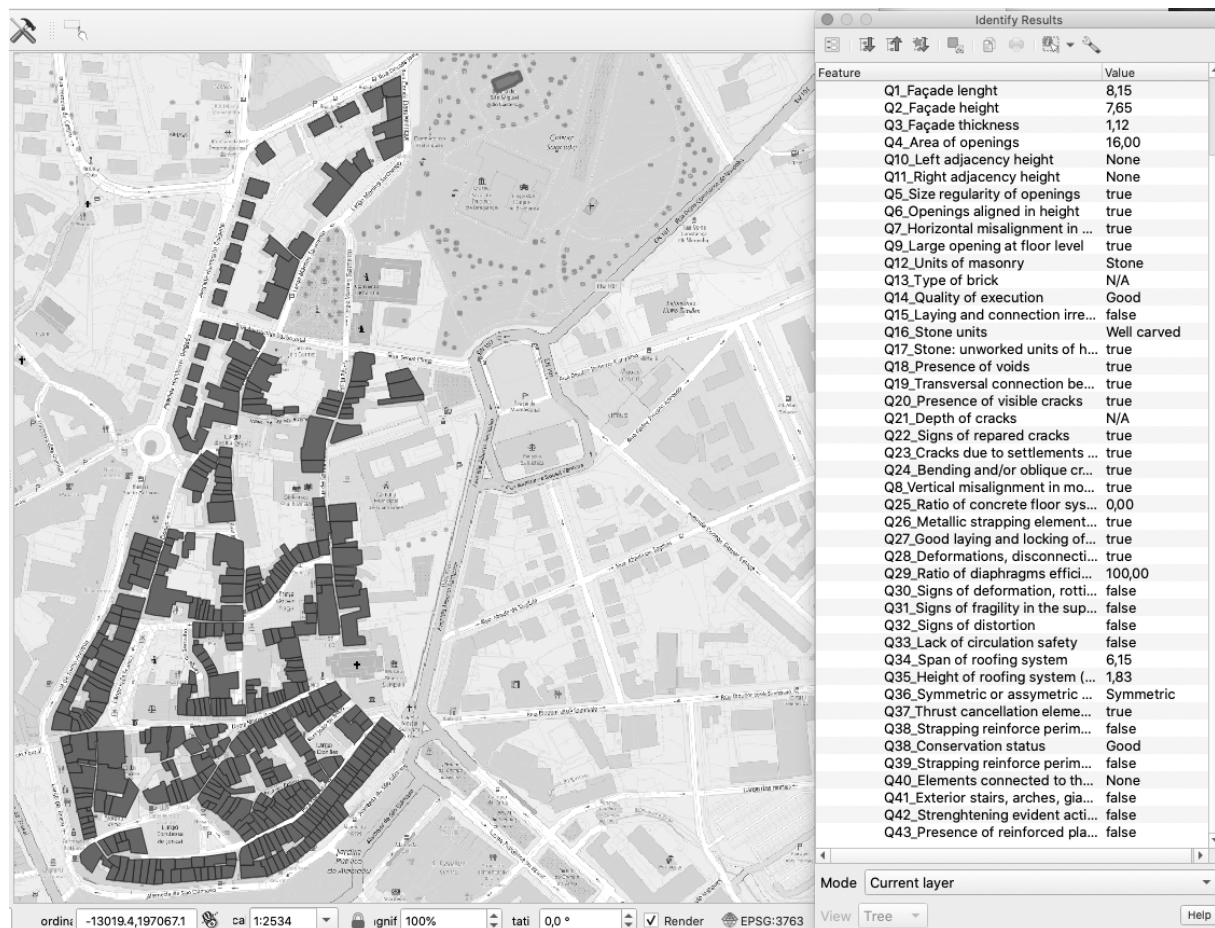


Figure 3.12: Screenshot of the QGIS interface displaying the survey of the Church of São Miguel.

Even if the data treatment for carrying the vulnerability assessment method exceeds the scope of this exercise, it is pertinent to note that the grading of the building can be carried out by feeding a simple conditional-based algorithm (even in a datasheet). This process can be repeated for covering sets of buildings, such as in an HUL. The information gathered during this process is shown in Table 3.4.

Query	Value	Query	Value	Query	Value	Query	Value	Query	Value
Q1	8.15	Q10	None	Q19	true	Q28	true	Q37	true/good
Q2	7.65	Q11	None	Q20	true	Q29	100	Q38	false
Q3	1.12	Q12	Stone	Q21	N/A	Q30	false	Q39	false
Q4	16	Q13	N/A	Q22	true	Q31	false	Q40	None
Q5	true	Q14	Good	Q23	true	Q32	false	Q41	false
Q6	true	Q15	False	Q24	true	Q33	false	Q42	false
Q7	true	Q16	Well carved	Q25	N/A	Q34	6.15	Q43	false
Q8	true	Q17	true	Q26	true	Q35	1.38	-	-
Q9	true	Q18	true	Q27	true	Q36	Symmetric	-	-

Table 3.4: Data obtained during the survey.

3.6 Discussion.

The above-proposed exercise illustrates a sequential workflow for contextualising an approach for the Historic Urban Landscape in the Aristotelian theory of the causes by departing from a specific and realistic set of attributes to be surveyed for reaching a specific purpose. This process is expected to occur with different sets of attributes and multiple purposes, according to the variety of actors, stakeholders, and agents that converge in the Historic Urban Landscape. This exercise accepts that the agents interested in the HUL depart from their own surveys and models. However, this example illustrates how the enlargement and enrichment of the database would open a wider horizon for exploring attributes that are not usually considered.

A worth noting issue identified during the process was the need to deconstruct some general attributes in smaller parts, namely those that consist of simple queries. This process is relevant in the context of data that different agents can further use. For example, we can accept that numerous agents would be interested in knowing the length of the façade while, in the example provided, this is a component used to evaluate some of the vulnerability assessment parameters, not a final product.

A certain dose of subjectivity was found when classifying the queries in the HUL causal structure. This is one of the challenges for the first steps of defining a causal structure. However, it is important to note that the addition of more queries and the identification of their interdependence permits clarifying the logical development of the structure. Even if there would be some difficulties for a priori classification, the immediate upper and lower-level analysis may help identify the suitability of the classification. A more extensive set of indicators and instances would certainly help the design of a robust structure. Furthermore, already existing criteria and classifications, such as those of the Industrial Foundation Class (IFC) for BIM models and Level of Detail (LoD) for urban 3D models, would help provide standardised frameworks during the causal structure design.

One of the implicit advantages of dividing the parameters into relatively simple queries is the compatibility of this approach with the proposed data acquisition procedure. Although, as demonstrated by the example provided, a relatively small survey may imply a wide set of queries, the proposed workflow permitted to easily acquire, store, and synchronise the information during an on-site campaign.

The use of the default types of data that a QGIS file accepts for characterising entities in a layer was found enough for programming the queries. Furthermore, no incompatibilities were found while carrying the complete process of the database setup, the cloud storage, the on-site data acquisition in a mobile device, and the online synchronisation. This kind of surveys can be developed on existing GIS databases.

Plus, it is not even necessary to have polygons or geometrical entities for acquiring information since any surveyor can store single points associated with a determined survey. This approach would be helpful in census and surveys non-related to buildings, such as urban furniture, vegetation, or events. Then, it is consistent with the flexibility and robustness needed for surveying the multiple layers of the HUL.

Some limitations found during the exercise were related to the impossibility of editing the attribute table from the app Input. This may be an issue if there is a problem while programming the survey. Another potential issue is that the information stored by a determined surveyor would overwrite existing data, namely when the file was not synchronised and a determined entity appears as empty. In fact, the workflow depends on a manual frequent refreshing of the file for visualising the latest changes in the file.

The complete experience would be enriched by the repetition of this process in the context of a very different survey related to the HUL for testing the enrichment and enlargement of the HUL causal structure when several and interdisciplinary approaches have occurred.

3.7 Final remarks.

The interest in understanding and analysing the historical city as a complex phenomenon has supported the development of the Historic Urban Landscape approach. This methodology is intended to unify the multiple ways of understanding and living the city, including the point of view and needs of multiple stakeholders, helping decision-making. The HUL approach's success primarily depends on the surveying and mapping of the natural, cultural, and human resources of the city.

There is no unique approach for documenting the HUL since the stakeholders need specific sets of information for their processes. However, some generalising approaches have been proposed. A feasible approach for reading and describing the HUL involves recognising it as a series of entities linked by causal relations. The analysis of these relations through the scope of the Aristotelian theory of the causes permits the establishment of logical structures for exploring specific dimensions of the urban phenomenon in a generalised framework, respecting the relations between the components. This categorisation and description process is valuable for organising the information generated from multiple actors, articulating a comprehensive description of the urban entity.

The Aristotelian causes approach, based on identifying the material, formal, efficient, and final causes of the constituent entities, permits to reach levels of detail of the descriptions as deep as necessary, nesting a series of surveys. The implementation of the Aristotelian causal structure for organising the information requires conceiving the HUL system as a series of nested instances. This exercise would be unusual in

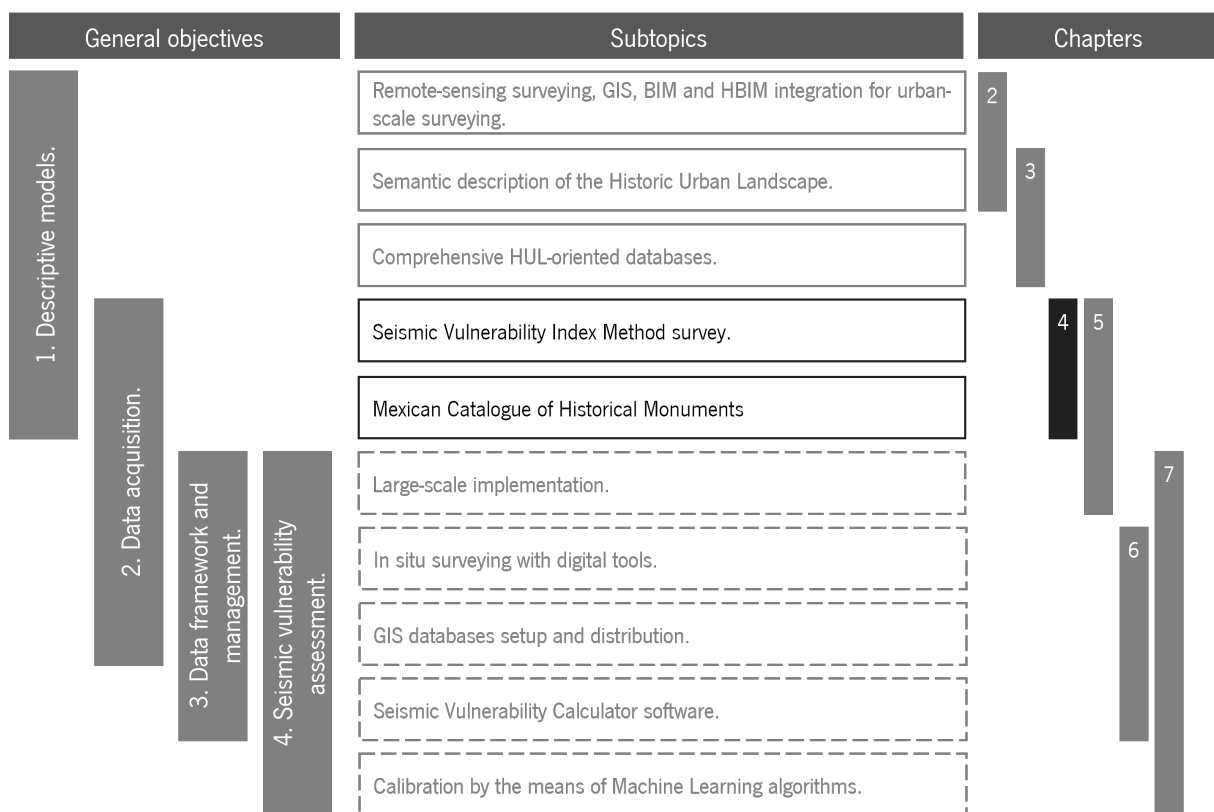
the context of specific and specialised approaches to the historical city but is especially meaningful while designing a common framework for understanding the HUL as a holistic, complex, and comprehensive set of phenomena. One of the interesting purposes of this approach is the potential conciliation and integration of already existing works and views on the historic city.

Resorting to a standardised framework to survey the city also allows that the parameters (deconstructed in basic instances and causal-related queries) can be investigated utilizing relatively simple means, such as attribute tables within QGIS databases.

Furthermore, the availability of open-source software and its integration with cloud-based storage permits sharing and managing GIS files from portable devices. This approach facilitates the on-site surveying of the city, which may support wide collaborative networks for documenting the HUL, reaching the goal of having a holistic, interdisciplinary, and complementary view of the historical city.

Chapter 4

Existing Catalogues for seismic vulnerability assessment of historical buildings.



R. Ramírez Eudave and T. M. Ferreira (2021) On the potential of using the Mexican National Catalogue of Historical Monuments for assessing the seismic vulnerability of existing buildings: a proof-of-concept study, Bulletin of Earthquake Engineering 19 (12) 4945–4978. DOI: 10.1007/s10518-021-01154-5

Abstract.

The possibility of characterising an existing building based on a limited set of attributes would permit building a semantical, graphical or even conceptual model that could serve as a reference for analytical purposes. Providing that the intent of the analysis and the evaluation procedures are consistent with each other and coherent with the description, it is plausible to assume that the data required to build such a conceptual model could be obtained by resorting, for example, to an ad-hoc survey composed of a set of pre-selected parameters. In the context of a growing interest in preserving Mexican cultural heritage, there has been a continuous effort to catalogue the buildings that, under the corresponding legal definition, are considered historical monuments; in this case, all constructions dated from the early 16th century until 1900. This catalogue has allowed putting together a comprehensive database of the Mexican architectonic heritage. Among other applications, this catalogue has been used to support intervention decision making, particularly in the sequence of recent seismic events in Mexico. Much of the information included in the current version of the catalogue is related to the buildings' structural characteristics, making it pertinent to discuss the suitability of using these data for feeding simplified vulnerability assessment methodologies. With this in view, the present chapter explores and discusses the feasibility of a transversal use of an index-based seismic vulnerability assessment approach for façade walls together with the Mexican National Catalogue of Historical Monuments. For such, the methodology—a pre-established vulnerability assessment approach for façade walls—was applied to a set of representative masonry buildings damaged by the 2017 Puebla earthquake. Furthermore, this chapter offers a proposal for enhancing the existing survey to obtain data that would permit to include a semi-quantitative index for vulnerability as a part of the current catalogue works.

4.1 Introduction.

The process of documenting cultural heritage should be inherent to any dissemination or protection action. Even if the strategies for describing a particular type of cultural asset (e.g., a building) are sometimes given as a matter of fact, the design of suitable and accurate methodologies must observe a series of circumstances for creating meaningful descriptions. In fact, each description's purpose (or set of descriptions) is determinant for selecting the representative descriptors of the entity, the data-acquisition strategies, and how information is stored, managed, and represented.

One of the potential purposes of a description is to characterise the vulnerability of an asset towards a specific hazard. The historical structures, a particular case of cultural assets, have been widely studied to understand and characterise their structural and seismic behaviour. If the representation is something that «stands for» or «takes the place» or something else [Hoskyns, 1934], then it is relevant exploring the components, strategies and approaches that would permit a wide set of application related to the assessment, management, and conservation of historical structures.

The interest in cataloguing the architectonic heritage has given a series of national and local models for characterising cultural assets. The comprehensive study of H. Sykes [1984] analysed and compared an extensive series of systems used for cataloguing immovable cultural assets, as summarised in (Table 4.1). Most of these systems were initially focused on acquiring a series of descriptors devoted to the location, identification, history, description, conservation status, and documentation of cultural assets.

Country	System name
Argentina	Sistema Automatizado de Inventario y Registro de Monumentos y Sitios (SIRAMS)
Canada	Canadian Inventory of Historic Building (CIHB)
France	Inventaire Général des Monuments et des Richesses Artistiques de la France (IGRAF)
India	Record of Protected Monuments and Sites, Archaeological Survey of India
Italy	Catalogo dei Beni Culturali
Japan	Ledger for Designated Cultural Property
Mexico	Catalogación Sistema Culhuacán
Morocco	Inventaire National du Patrimoine Culturel
United States	Urban Cultural Resources Survey (New York UCRS)
Poland	System of Inventorying Historical Monuments
Zambia	Zambia National Site Index

Table 4.1: Summary of inventorying systems by country. Adapted from H. Sykes [1984].

The concerns about the progressive and unnoticed loss of cultural heritage in Mexico, particularly in remote and difficult access territories, led to the creation of a comprehensive and robust model for characterising the constructions threatened by environmental agents and/or abandonment. The National

Catalogue for Historical Monuments, whose initial scope was exclusively documental, has gradually become a first-approach source for any activity related to the conservation and intervention on the cultural heritage. The catalogue is curated and updated by the National Institute for Anthropology and History (INAH) since 1984.

Besides the architectonic characterisation of the historical structures, there has been a great interest in the vulnerability-oriented surveying of cultural assets. In fact, the idea of having an integrated and multi-disciplinary approach for an accurate seismic vulnerability assessment has been extensively explored from diverse points of view, namely focused on masonry constructions.

In this regard, it is pertinent to analyse the critical role of understanding the past of a structure when diagnosing damages and pathologies or performing structural assessment, as discussed by Barbieri et al. [2017], and to learn from past experiences, such as the one presented by Ponte et al. [2021], who have put in practice an interdisciplinary five-step approach to assess the seismic vulnerability of the National Palace of Sintra, in Portugal: historical data analysis and field survey; experimental campaign and characterisation of the seismic action; experimental test and dynamic identification of the structure; numerical modelling and calibration and; seismic assessment based on nonlinear static and dynamic analyses.

The relevance of having a «knowledge path» guided the exploration that Bento [2019] used for the seismic assessment of masonry buildings in Lisbon. The definition of four well-defined typologies (based on chronological, material, and structural parameters) was the base for a set of fragility curves associated with typological structural performances. The Italian Risk Map (Carta del Rischio), is another paradigmatic example of a comprehensive database used to contextualise the seismic vulnerability of cultural assets [Bartolomucci and Cacace, 2009].

In the context of urban analysis, some worthy of mention concepts and approaches have been proposed over the last years for vulnerability assessment and risk mitigation. The concept of «minimum urban structure», which relates to the recovery of a city after a seismic event [De Paoli, 2012], or the concept of «limit condition for emergency», which represent the maintenance of critical services and connections [Dipartimento della Protezione Civile, 2021], are two interesting examples coming from Italy—a country with a very rich experience in post-earthquake data acquisition.

The experiences of numerous events, such as the ones of Friuli (1976), Irpinia (1980), Abruzzo (1984), Marche (1997) and Pollino (1998), permitted the continuous refinement of post-event damage surveying procedures [Goretti and Di Pasquale, 2002]. More recently, in 2009, the L'Aquila earthquake was a tremendous source of data and information, particularly for the characterisation of the seismic behaviour of masonry structures [Rosti et al., 2018]. Last but not least, it is worth stressing the role of simplified seismic

vulnerability assessment approaches for assessing the vulnerability of large building stocks, particularly of the index-based methods [Julià and Ferreira, 2021].

Among many examples that could be mentioned here, variations of index-based methods have been applied in various historical cities: Seixal, Portugal [Ferreira et al., 2013], Annaba, Algeria [Athmani et al., 2015], Horta, Portugal [Ferreira et al., 2017c], Osijek, Croatia [Hadzima-Nyarko et al., 2016], Timisoara, Romania [Mosoarca et al., 2019], Naples, Italy [Chieffo et al., 2021], etc.; in a clear demonstration of the adaptability, versatility and suitability of such methodology for multiple typological varieties. Even so, and despite the above-mentioned examples, the use of regular catalogue-oriented databases usable for feeding simplified seismic vulnerability assessment approach is still scarce, particularly in the Central Southern American and Mexican contexts.

In an attempt to contribute to bridging this gap, the present chapter offers an overview of the current strategies for documenting cultural assets in the Mexican, namely regarding the descriptive sense of the existing catalogues. Furthermore, the use of a pre-existing façade-based approach for assessing the seismic vulnerability of historical constructions based on a series of geometrical and structural parameters (descriptors) is tested and discussed herein, particularly considering the geographical framework in which the assumptions of the approach were contextualised. Besides other relevant side aspects, the main interest of this approach lies in the a priori similarity between the set of descriptors used in this methodology and the fields of the INAH's catalogue, suggesting potential compatibility between both.

A set of nine traditional masonry buildings damaged by the 2017 Puebla earthquake, which struck the central area of the Mexican territory on September 19, 2017 [Servicio Sismológico Nacional, 2017], were used in this proof-of-concept analysis. Field observed damages are compared with analytical-estimated damages, allowing to discuss the suitability and potential impacts that a large-scale implementation may reasonably have based on evidence. On the other hand, it also permits identifying and discussing the major challenges associated with the practical use of this approach, proposing a route for future works and developments. This exercise represents an innovative attempt of implementing a large-scale structural assessment based on pre-existing and available data, which, as proved herein, has the potential to be used to assess a large number of historical constructions in Mexico, including countless vernacular and non-designed highly vulnerable constructions.

4.2 The Mexican National Catalogue for Historical Monuments.

The Mexican National Institute for Anthropology and History (Instituto Nacional de Antropología e Historia—INAH) is responsible for cataloguing and producing documentation related to the historical monuments, as determined in its organic law, comprising any construction from the early 16th century to 1900. To do this, there is a progressively enhanced model of survey sheets through which relevant information is collected and processed. The first catalogues were developed in the 1980s decade, and there have been successive stages of evolution, namely by using digital platforms and databases.

Nowadays, the National Catalogue for Historical Monuments [Dirección de Medios de Comunicación, 2018] includes more than 100,000 constructions. The primary objective for this activity was documenting buildings that may have been highly damaged or destroyed either by a hazard event or as a result of abandonment situations. However, the catalogue has multiple applications for heritage management purposes and historical documentation. Among other uses, it can be a valuable source of information for stakeholders and decision-makers.

Currently, the standardised catalogue datasheet includes a series of data fields, namely the identification of the cultural asset, its localisation, legal regime of property, religious adscription (if any), historical information, third documental sources, a brief architectonic description, general material characteristics and some structural and construction generalities.

This information is also complemented by one or two pictures (one of the main façade and a detail), one representative and simplified architectonic plan and a localisation map. The output model of these sheets was a one or two-pages document with the most relevant fields. However, those sheets were exclusively produced inside the INAH informatic network and were only accessible on-demand, limiting the public access to the catalogue. In recent years, most of the available sheets were integrated into an official public website, which has progressively incorporated the entire database, Fig. 4.1.

Data acquisition for updating and creating datasheets is mostly based on on-site works, supported by survey sheets that comprise a set of manually fulfilled fields. However, such a process poses several challenges related, for example, with the human resources and logistics-related aspects, including the accessibility to the constructions, which can limit the amount and quality of the information collected during the surveys.

The current survey datasheet considers geographical information, identification of the building, property regime, historical information, architectonic and structural characteristics and exposition to hazards, among others:

CONSULTA PÚBLICA DEL CATÁLOGO NACIONAL DE MONUMENTOS HISTÓRICOS INMUEBLES

MONUMENTO HISTÓRICO

Clave de Ficha: I-15-00032

Nombre: Antigua estación de ferrocarril de El Oro

Tipo y subtipo de ficha: Inmueble Civil

Descargar detalle

Citar ficha

Contáctanos

Fachadas, 2015.

Detalles del interior, 2015.

Planta arquitectónica, 2015.

Croquis de localización. Fuente: Plano catastral.

Expandir todos

TIPO DE FICHA

LOCALIZACIÓN

IDENTIFICACIÓN

ASPECTOS LEGALES

INFORMACIÓN HISTÓRICA

FUENTES CONSULTADAS

MONOGRAFÍA

DESCRIPCIÓN ARQUITECTÓNICA

CARACTERÍSTICAS FORMALES Y MATERIALES

FECHA DE ELABORACIÓN / FECHA DE ACTUALIZACIÓN

CENTRO DE DOCUMENTACIÓN DE LA CNMH.

PLANOTECA DEL AHJE

ARCHIVO HISTÓRICO JORGE ENCISO

FOTOTECA CONSTANTINO REYES-VALERIO

Cerrar

Esta ficha contiene la información que se encuentra en la Base de Datos del Catálogo Nacional de Monumentos Históricos Inmuebles, la cual constituye una herramienta de trabajo que el Instituto Nacional de Antropología e Historia utiliza para la identificación de inmuebles con valor patrimonial, asimismo es un instrumento de soporte técnico, documental y académico, en constante actualización, que permite formular y promover programas para la protección, conservación y difusión del patrimonio histórico edificado. La utilización de este material es únicamente con fines de consulta.

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Figure 4.1: Screenshot of the Catalogue's online public platform with the fields contained in the database: <https://www.catalogonacionalmhi.inah.gob.mx/>

- Type of datasheet.
 - Religious/funerary/other.
- Localisation
 - State, Municipality, Region.
 - Street and number.
 - Type and name of settlement/village/neighbourhood.
 - Postal code.
 - Surrounding streets (including a schematic localisation plan).
 - National Monument Zone (if any).
 - Public Property Register number.
 - ITRF92 or WGS84 geographic coordinates, including height.
- Identification
 - Classification as historical (built before 1900) or cultural monument (built after 1900).

- Original use. Category: domestic, commercial and services, public administration, justice facilities, financial and custom facilities, military building, culture and sports, schools, health facilities, religious, funerary, commemorative, civil infrastructure, hydraulic infrastructure, domestic and craft industry, agriculture and production, parks and gardens, public spaces; Genre (a subtype of the category, if any).
- Architectonic typology (if any).
- Name, when the building has a well-known denomination.
- National Monument Zone (if any).
- Present use. Category: domestic, commercial and services, public administration, justice facilities, financial and custom facilities, military building, culture and sports, schools, health facilities, religious, funerary, commemorative, civil infrastructure, hydraulic infrastructure, domestic and craft industry, agriculture and production, parks and gardens, public spaces; Genre (a subtype of the category, if any).
- Architectonic typology (if any).
- Urban use classification: housing, commerce, services, industry, infrastructure.
- General and specific use, if any.
- Lost asset. When there is an existing datasheet or register of a building that no longer exists when the survey is performed.
- Legal aspects
 - Property: private or public. If public, user and responsible for the building.
 - Federal register and property register.
 - Federal (national) Declaration as a National Historic Monument.
 - Listed in a Historic Monuments Zone.
 - Located but not listed in a Historic Monuments Zone.
 - State declaration as monument / relevant building.
 - Municipal declaration as monument / relevant building.
 - Regulated by an urban plan.
 - Other registers existing in different databases or archives.
- Religious and administrative aspects (if any).
 - Original patronage, devotion or advocacy.
 - Present patronage, devotion or advocacy.
 - Foundation.

- Administrative adscription.
- Category: basilica, cathedral, parish, vicary, chapel, sanctuary, convent, hermitage, mission, bishopric, inquisition, mosque, synagogue, temple, etc.
- Religious order, if any.
- Historic information
 - Construction date (century).
 - Date of interventions (century).
 - Previous unrelated constructions.
 - Type of structure (pre-Hispanic, historical, other).
 - Location of the previous unrelated construction, if any.
 - Historical information (brief).
- Sources
 - Testimonies, archives, documents, inscriptions, etc.
- Environment
 - General description.
- General terrain attributes
 - Number of storeys.
 - Total, built and free surface (in square meters).
- Architectonic description.
 - Text field for stylistic and semantic descriptions.
 - Formal and material properties.
 - Architectonic plan: basilica, central patio, sided patio, Greek cross, Latin cross, polygonal, radial, single corridor construction, single nave, other.
 - Main façade:
 - * Material: Adobe, brick masonry, stone masonry, tiles, metallic sheet, stone, metals, other.
 - * Description.
 - * Conservation state (good, regular, bad).
 - Vertical structure:
 - * Material: Adobe, brick masonry, stone masonry, tiles, metallic sheet, stone, metals, other.
 - * Description.

- * Conservation state (good, regular, bad).
 - * Thickness (up to two measures, minimum and maximum, if applicable) .
- Floor structure:
 - * Material: wood structure, metallic structure, iron, bricks, reinforced concrete slab, stone, mixed systems, etc.
 - * Geometry: vault (and its varieties), plain
 - * Approximate height (up to two measures, minimum and maximum, if applicable).
 - * Description.
 - * Conservation state (good, regular, bad).
- Ceiling:
 - * Material: wood structure, metallic structure, iron, bricks, reinforced concrete slab, stone, mixed systems, etc.
 - * Geometry: vault (and its varieties), plain, oblique, etc.
 - * Approximate height (up to two measures, minimum and maximum, if applicable).
 - * Description.
 - * Conservation state (good, regular, bad).
- Floor finishing:
 - * Material: cement, tiles, stone, brick, ceramic, wood, etc.
 - * Description.
 - * Conservation state (good, regular, bad).
- Stairs:
 - * Material: cement, tiles, stone, brick, ceramic, wood, etc.
 - * Geometry.
 - * Description.
 - * Conservation state (good, regular, bad).
- General state of conservation
- Mobile cultural assets
 - If any
- Risk Analysis (exposure, subtype and emergency plan, if applicable)
 - Geologic (landslides, earthquakes, tsunamis, vulcanism)
 - Hydrometeorological (hail, frost, terrain sinking, hurricanes, river or rain flood, snow, drought, storms, extreme winds)

- Physical-chemical (explosions, toxic leaks, fires, radiation)
- Sanitary (pollution, epidemics, plagues)
- Societal-organisational (aerial accidents, maritime accidents, terrestrial accidents, massive people concentrations, electricity interruption, manifestations, terrorism, etc.
- Electric facilities, conditions and observations.
- Hydraulic and drainage facilities, conditions and observations.
- Gas facilities, conditions and observations.
- Object susceptible to failing or slip, level of danger associated
- Emergency stairs, state and observations
- Fire combat equipment, existence and observations
- Safeguard of cultural assets, present state and observations
- Signals, existence, conditions and observations
- External surrounding hazard sources, if any
- Priority of attention
 - Urgent, corrective, preventive
 - General observations
- Attachments
 - Localisation plan
 - Architectonic schematic plan
 - Photography of the main façade
 - Photography of a secondary façade, historic photography or interior detail
 - Others (maps, videos, documents)
- Surveyors
 - Name, adscription, supervision

The information on relevant structural and seismic performance-related aspects is limited since, as mentioned, the catalogue has a different purpose. Nevertheless, the catalogue data are potentially compatible with the use of simplified structural and vulnerability assessments approaches, namely those based on index-based indicators. After high-scale seismic events, more attention has been paid to the need for assessing the seismic vulnerability of historical constructions.

On the 7th of September, 2017, an $M_w = 8.2$ seismic event hit the south of Mexico. Just a few days after, on the 19th of September, an $M_w = 7.1$ earthquake hit the centre of the country, affecting Mexico City and the surrounding areas. In an ominous coincidence, this earthquake coincided with the

32nd anniversary of the most destructive earthquake in the history of Mexico City, and it happened just a few hours after the commemorative event. Preliminary information declared around 150,000 affected buildings [Alberto et al., 2018].

In the sequence of this seismic crisis, the information contained in the National Catalogue of Historical Monuments was used to conduct a preliminary estimation of the damages on the affected historical assets. From a total of 2340 damaged buildings, 1450 were labelled with moderate and severe damages. 61.4% of the damaged buildings were located in the states of Oaxaca, Puebla and Morelos [San Juan et al., 2017]. These states figure respectively in the third, fifth and seventeenth place in the 2015 national marginalisation index [Consejo Nacional de Población, 2016], which is a relevant aspect to explain the profound impact of these events in social and economic terms, as well as the challenge for the resilience process after the events.

The recurrence of seismic events in Mexican territory is a significant threat for a broad universe of buildings with unknown seismic safety, and the reason why the possibility of using the information contained in the catalogue to support a nationwide seismic vulnerability assessment campaign is very promising and deserves in-depth analysis.

4.3 Seismic vulnerability assessment.

There is currently an increasing interest in sustainable urban development, which is frequently associated with the reuse of existing constructions. However, the actions on existing constructions must be preceded by knowledge about their present state and structural safety. This information is not only relevant for carrying actions on individual buildings, but also for studying phenomena that involves clusters of historical constructions, such as the case of historical centres. The information regarding entire groups of buildings' behaviour is especially meaningful for understanding post-seismic scenarios since the consequences of damages on individual constructions will configure entire urban-scale assessments.

The anticipation of urban-scale effects of earthquakes is relevant for developing strategies on the use and management of the historical assets as cultural and economic resources. Forecasting damages would help to minimise losses by identifying the assets at risk, defining intervention priorities, and adopting appropriate preventive measures and emergency plans.

Despite the numerous developments in structural analysis of historical constructions, the obtention of urban-scale assessments is still challenging, namely due to the wide diversity of typologies, conservation states, and singularities inherent to historical constructions.

Most of the existing assessment methods can be generically framed into three main groups: empirical (based on records, observations and meaningful typological features), analytical (based on simplified mechanic analysis) and hybrid, including sources such as expert judgment [Calvi et al., 2006]. Some approaches are intended to establish correlations between seismic intensities and estimated damages according to a limited set of architectonic and structural parameters, which facilitate to carry urban-scale assessments. These parametric approaches represent a reasonable effort in the context of wide samples, mostly as a first-level approach [Ferreira et al., 2019]. The parametric approaches are intended to present ranges for estimated damages as a function of specific earthquake intensity and an individualised vulnerability index.

4.3.1 Index-based methodologies to assess masonry buildings.

Seismic vulnerability is a component of the seismic risk, together with the hazard—which can be defined as the probability of occurrence of a determined intensity seismic event in a certain site and during a determined period [Carreño et al., 2007]—and the exposure—which is related to the set of material assets and human lives that would be potentially affected.

A comprehensive characterisation of risk depends thus on an accurate assessment of the vulnerability, which represents the sensitivity (expressed as a grade of damage) that a building would have towards a specific seismic event. In addition, out of the three risk components, vulnerability is the only one possible to be reduced through engineering intervention. Therefore, reducing the exposed assets' vulnerability is the most viable and efficient means of reducing the overall seismic risk.

A relevant system for assessing the seismic vulnerability of constructions is the Vulnerability Index Method, originally designed and applied in Italy. Developed in 1994 by the National Group for the Defence from Earthquakes (Gruppo Nazionale per la Difesa dai Terremoti—GNDT), this approach aimed at facilitating the data acquisition of existing buildings by means of a comprehensive but straightforward survey datasheet [Benedetti and Petrini, 1984, Gruppo Nazionale per la Difesa dai Terremoti—GNDT, 1994]

The predominance of masonry among historical buildings, a material whose characterisation and evaluation are still difficult, represents a significant challenge when assessing their seismic vulnerability. Nevertheless, some general assumptions may be the basis for establishing simplified behaviour assumptions, such as a brittle response in tension, a frictional response in shear and anisotropy [Roca et al., 2010]. Based on the analysis of a large volume of damage data, a set of characteristics has been highlighted as especially meaningful for influencing the seismic response of masonry buildings. This set of attributes is the base for a field survey in which every parameter is classified with four different possible grades that

will feed an arithmetic calculation for obtaining a global index [Calvi et al., 2006]. Grades express how a determined condition increases or decreases the vulnerability of the constructions.

Initially composed of eleven evaluation parameters, the approach has been reworked, expanded and calibrated by multiple authors over the last years. More recently, Ferreira et al. [2017c] and Maio et al. [2020] have proposed an updated version of this approach with fourteen parameters, see Table 4.2. Similarly to the original version of the method, the overall vulnerability index is given by the sum of the products of each parameter vulnerability class multiplied by a given weight that reflects the relative importance of the parameter in the overall formulation, see Eq. (4.1). The independence between the class values and the weights permits adjusting and calibrating the methodology to local typologies' specificities in which each parameter may have a more significant or a smaller impact on the buildings' seismic behaviour.

Parameters	Class C_{vi}				Weight p_i	Relative weight
	A	B	C	D		
Group 1 Structural building system						50/100
BP1. Type of the resisting system	0	5	20	50	2.50	
BP2. Quality of the resisting system	0	5	20	50	2.50	
BP3. Conventional strength	0	5	20	50	1.00	
BP4. Maximum distance between the walls	0	5	20	50	0.50	
BP5. Number of floors	0	5	20	50	0.50	
BP6. Location and soil condition	0	5	20	50	0.50	
Group 2 Irregularities and interaction						20/100
BP7. Aggregate position and interaction	0	5	20	50	1.50	
BP8. Plan configuration	0	5	20	50	0.50	
BP9. Height regularity	0	5	20	50	0.50	
BP10. Wall façade openings and alignment	0	5	20	50	0.50	
Group 3 Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	
BP12. Roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						12/100
BP13. Fragilities and conservation status	0	5	20	50	1.00	
BP14. Non-structural elements	0	5	20	50	0.75	

Table 4.2: Vulnerability Index parameters, according to the calibration of Ferreira et al. [2017c].

$$I_{vf}^* = \sum_{i=1}^{14} c_{vi} p_i \quad (4.1)$$

The parameters are divided into four main groups: generalities of the structural system, irregularities and interaction, flooring and roofing systems, and conservation status and non-structural elements. Each parameter is associated with a specific grade for classification purposes. In the context of Mexican constructions, a proposal of adaptation has been explored by Salazar and Ferreira [2020]. In this work, the authors have reviewed and adapted the original formulation of every vulnerability parameter in order to make them suitable to the typologies and the codes currently in force in Mexico, such as the Mexico City Building Code (Reglamento de Construcciones para el Distrito Federal–RCDF), the National Institute for Anthropology and History (INAH) and the National Centre for Prevention of Disasters (Centro Nacional para la Prevención de Desastres–CENAPRED) recommendations. Each one of the parameters contains a series of qualitative or quantitative conditions that guide the selection of a determined vulnerability class. However, certain conditions may be unclear even with the help of the guides. Details on the evaluation parameters that compose this adapted approach have been extensively described by Salazar [2018] and are included in Appendix A.

4.3.2 A vulnerability Index Method to assess the seismic vulnerability of façade walls.

To fulfil the survey datasheet is always a very demanding and challenging task for cataloguers due to the above-mentioned time, human resources and accessibility limitations. In fact, a large set of situations may prevent the surveyor from covering all the fields that compose the sheets. A relatively common strategy for dealing with the inaccessibility to buildings is to only gather information from the part of the building that is fully visible from the outside—the façades. A relevant number of entries of the National Catalogue of Historical Monuments are indeed in this situation. Nevertheless, this information is still potentially valuable for vulnerability assessment purposes.

The methodology developed and calibrated by Ferreira et al. [2017b], and later applied by Aguado et al. [2018], is a variation of the Vulnerability Index Method for an assessment based on the information exclusively from the façade walls. This adaptation is mostly addressed to reveal the relative likelihood of the activation of out-of-plane mechanisms of collapse, which would also be meaningful in post-disaster scenarios. For example, allowing to obtain valuable urban-scale information, such as debris accumulation on the streets.

This adaptation was initially developed and validated by Ferreira et al. [2014], based on the analysis of post-seismic data for identifying construction parameters that influence the level of damage suffered by masonry façades. The original work considered ten parameters associated with four classes and cor-

responding weights, based on the GNDT II approach. The application of this approach in 672 buildings permitted more refined vulnerability functions and curves. The suitability of this method was validated through its comparison against simplified mechanical models. Further calibrations of this method, such as the ones of Ferreira [2015] and Ferreira et al. [2015], led to the current 13-parameter version of the method (Table 4.3). Like the buildings' approach, the vulnerability index for façade walls is obtained through the weighted sum of the 13 parameters class value C_{vi} multiplied by their corresponding weight factor P_i , which describes their relative importance Eq. (4.2)—the description of the vulnerability classes of each of the thirteen parameters that compose the method is provided in Appendix A. The vulnerability index is the base for the further estimation of damage grades.

Parameters	Class C_{vi}				Weight p_i	Relative weight
	A	B	C	D		
Group 1 Façade geometry, openings and interaction						16.7/100
FP1. Geometry of façade	0	5	20	50	0.50	
FP2. Maximum slenderness	0	5	20	50	0.50	
FP3. Area of openings	0	5	20	50	0.50	
FP4. Misalignment of openings	0	5	20	50	0.50	
FP5. Interaction between continuous façades	0	5	20	50	0.25	
Group 2 Masonry materials and conservation						31.5/100
FP6. Quality of materials	0	5	20	50	2.00	
FP7. State of conservation	0	5	20	50	2.00	
FP8. Replacement of original flooring system	0	5	20	50	0.25	
Group 3 Connection efficiency to other structural elements						33.3/100
FP9. Connection to orthogonal walls	0	5	20	50	2.00	
FP10. Connection to horizontal diaphragms	0	5	20	50	0.50	
FP11. Impulsive nature of the roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						18.5/100
FP12. Elements connected to the façade	0	5	20	50	0.50	
FP13. Improving elements	0	5	20	50	-2.00	

Table 4.3: Parameters and vulnerability classes, according to Aguado et al. [2018].

$$I_{vf}^* = \sum_{i=1}^{13} c_{vi} p_i \quad (4.2)$$

4.4 Towards an integrative survey based on the catalogue.

Breaking down the two seismic vulnerability assessment methodologies, presented in the previous sections, and the data contained in the National Datasheet Catalogue, it is possible to observe that a significant part of the attributes, whose collection is already part of the current surveying actions, can be efficiently used to input most of the parameters that compose the approaches (Figure 4.2). Furthermore, the conceptual formulation of each of these evaluation parameters would improve or enrich the datasheet description, which is currently vague and imprecise—for instance, by providing semi-quantitative guides for assessing if a determined opening alignment is irregular or not.

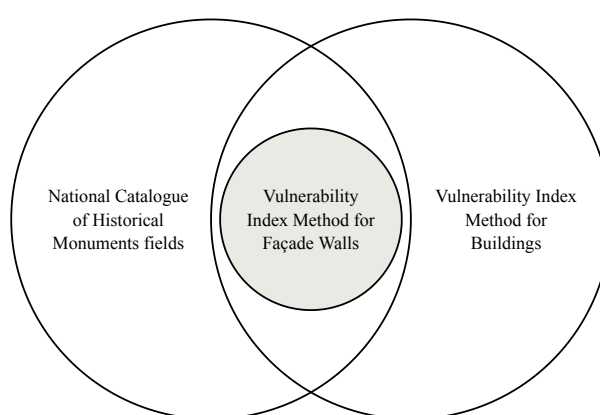


Figure 4.2: Venn diagram illustrating the overlapping between the methodologies and the Catalogue.

As shown in Figure 4.3 and Figure 4.4, the current version of the INAH datasheet covers most of the parameters that compose the Vulnerability Index Method (with the exception of BP6, since there is no information about the foundations). This means that only some minor modifications must be done, namely in what regards to the organisation and definition of the fields, so that this information can be used to assess seismic vulnerability resorting to the two approaches analysed herein. It is convenient to remark that some aspects, such as the mechanical properties of materials (needed for assessing BP3), would need the use of external references in the construction codes or characteristic values found in literature, such as the ones proposed by Meli [1998] according to the characterisation of the masonry works.

As shown in Figure 4.5, the systematisation that would constitute a bridge between both methodologies is to include the grade-based system as a part of the current survey model. In fact, many of the parameters can be graphically represented as options, similar to the model proposed by Giuliani [2020]. Even accepting that most of the information is already there to be used, an adequate adaptation of the field survey would permit systematising information in a more efficient manner allowing for the eventual implementation of automatised data treatment and analysis procedures.

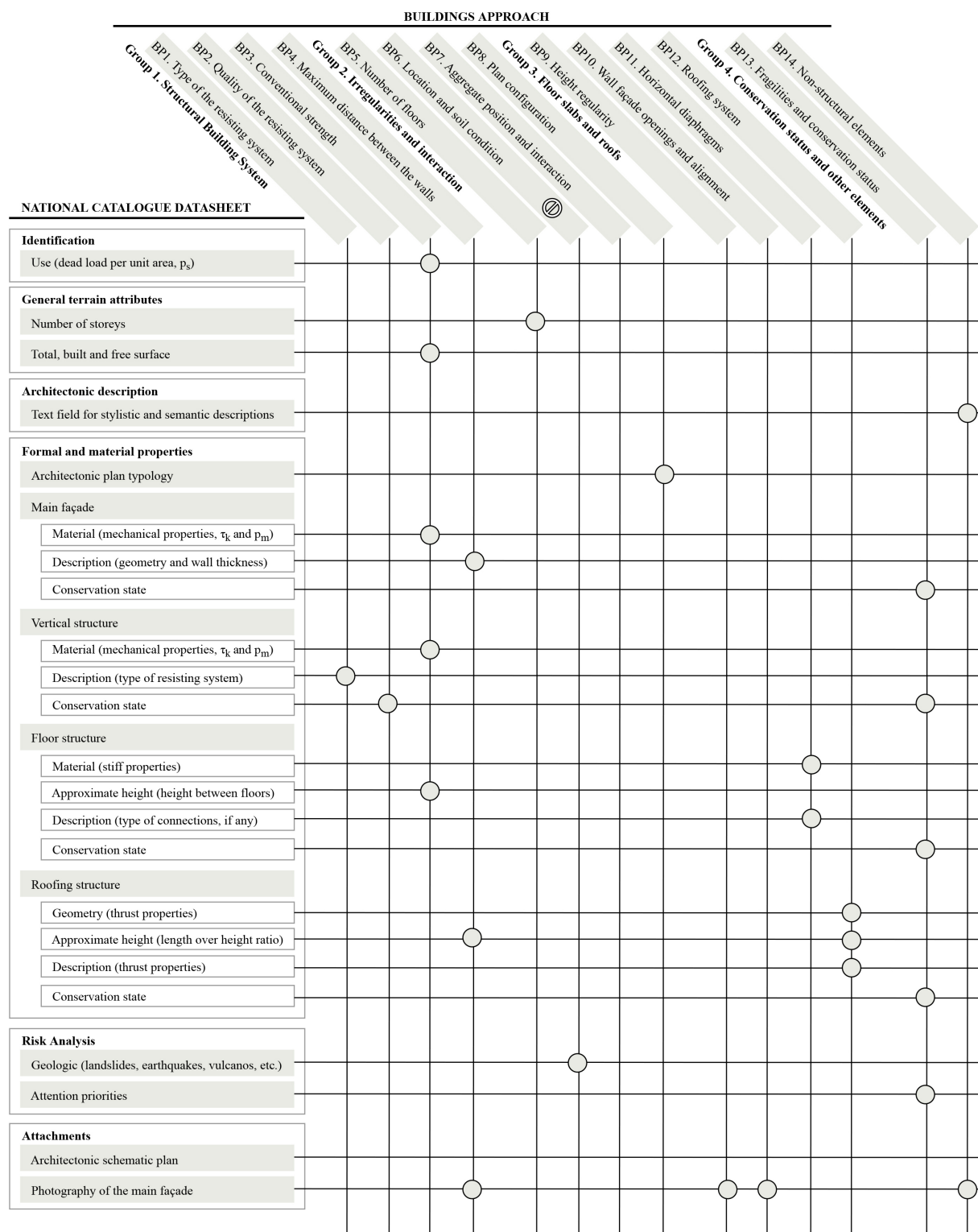


Figure 4.3: Compatibility analysis between the building approach's parameters and the INAH datasheet model.

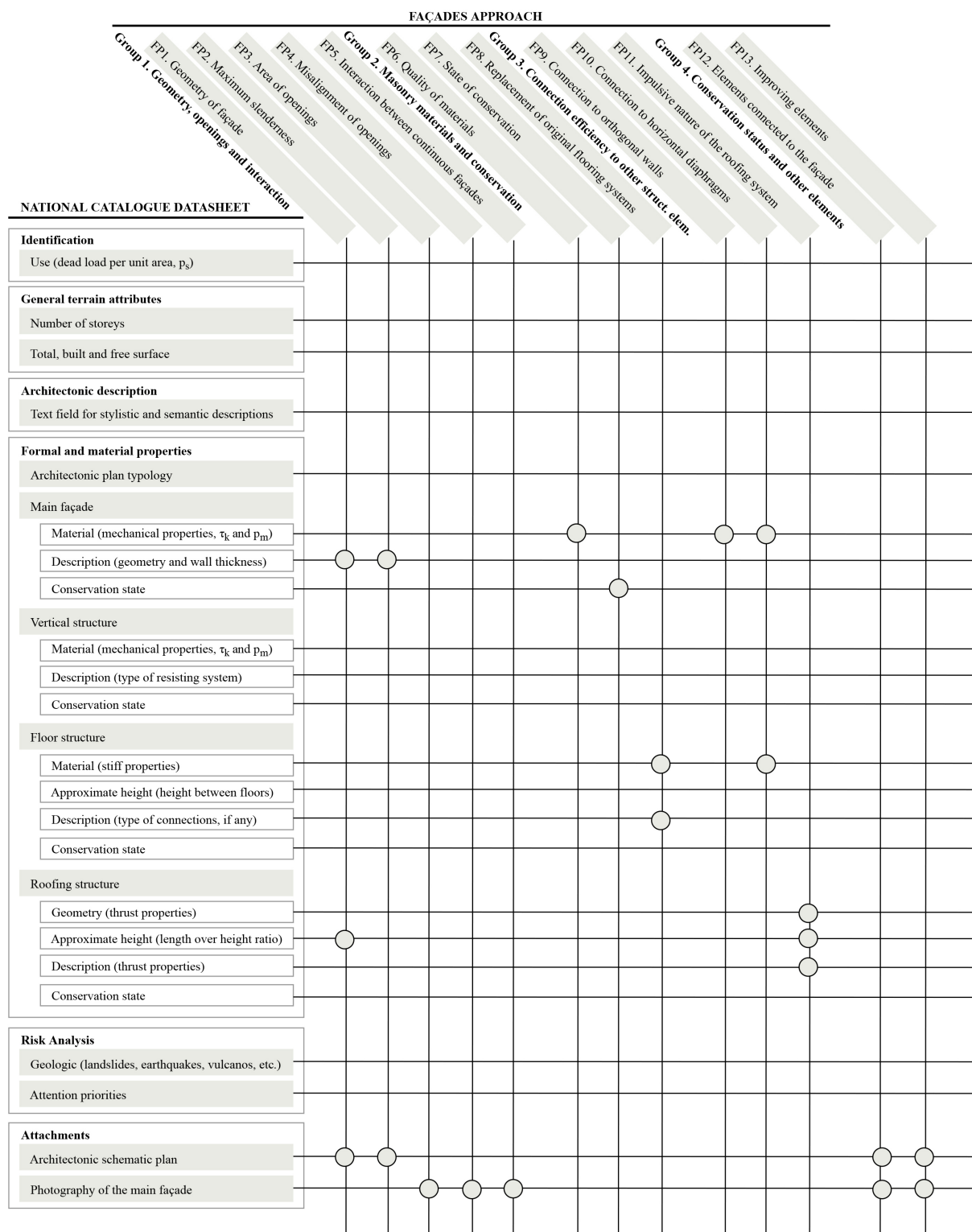


Figure 4.4: Compatibility analysis between the façade approach's parameters and the INAH datasheet model.

SURVEY FORM FOR MASONRY BUILDINGS		Date Surveyor(s)																																				
IDENTIFICATION Municipality ID Aggregate⁽¹⁾ ID Structural Unit⁽¹⁾ ID Facade⁽¹⁾ Is it cultural heritage? ☐ Listed ☐ Non listed FUNCTION/USE ☐ Annex ☐ Commercial ☐ Deposit/garage ☐ Public service ☐ Residential ☐ Tourism ☐ Unused ☐ Other _____ Is it an emergency land use? ☐ yes ☐ no If yes, specify _____ (school, healthcare, public security, municipality, other)																																						
GEOMETRY OF THE FACADE General dimensions Openings <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th style="width: 30%;">L⁽²⁾ [m]</th> <th style="width: 10%;">i⁽⁹⁾</th> <th style="width: 20%;">w_i⁽¹⁰⁾ [m]</th> <th style="width: 40%;">h_i⁽¹¹⁾ [m]</th> </tr> </thead> <tbody> <tr><td>H⁽³⁾ [m]</td><td></td><td></td><td></td></tr> <tr><td>H_{gable}⁽⁴⁾ [m]</td><td></td><td></td><td></td></tr> <tr><td>T_{bottom}⁽⁵⁾ [m]</td><td></td><td></td><td></td></tr> <tr><td>T_{top}⁽⁶⁾ [m]</td><td></td><td></td><td></td></tr> <tr><td>N stories⁽⁷⁾</td><td></td><td></td><td></td></tr> <tr><td>N openings⁽⁸⁾</td><td></td><td></td><td></td></tr> <tr> <td>☐ (12) </td> <td></td> <td></td> <td></td> </tr> <tr> <td>☐ </td> <td></td> <td></td> <td></td> </tr> </tbody> </table> DRAWINGS Elements on the facade⁽¹³⁾ (decorations, lamps, cables, equipment, balcony, pots, other) Id photos⁽¹⁴⁾			L ⁽²⁾ [m]	i ⁽⁹⁾	w _i ⁽¹⁰⁾ [m]	h _i ⁽¹¹⁾ [m]	H ⁽³⁾ [m]				H _{gable} ⁽⁴⁾ [m]				T _{bottom} ⁽⁵⁾ [m]				T _{top} ⁽⁶⁾ [m]				N stories ⁽⁷⁾				N openings ⁽⁸⁾				☐ (12)				☐			
L ⁽²⁾ [m]	i ⁽⁹⁾	w _i ⁽¹⁰⁾ [m]	h _i ⁽¹¹⁾ [m]																																			
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T _{top} ⁽⁶⁾ [m]																																						
N stories ⁽⁷⁾																																						
N openings ⁽⁸⁾																																						
☐ (12)																																						
☐																																						
STRUCTURAL MATERIALS (I) Walls of the facade ☐ Disorganised irregular stone masonry (pebbles, irregular and erratic stones) ☐ Ashlars roughly worked rubble masonry ☐ Squared stone blocks masonry with good texture ☐ Brick masonry and lime mortar ☐ Hollow brick masonry with cementitious mortar ☐ Hollow brick masonry ☐ Hollow brick masonry with dry joints ☐ Hollow concrete or expanded clay masonry ☐ Hollow concrete masonry Brick holes [%] ☐ <45 ☐ 45-65 ☐ > 65 Mortar quality ☐ L⁽¹⁵⁾ ☐ M⁽¹⁵⁾ ☐ H⁽¹⁵⁾ Transversal brick connections ☐ L ☐ M ☐ H Level of maintenance ☐ L ☐ M ☐ H Connections ☐ Floor-to-wall connections⁽¹⁶⁾ ☐ Wall-to-wall connections (perpendicular walls)⁽¹⁷⁾ Damage patterns Walls⁽¹⁸⁾ Lintels⁽¹⁹⁾ STRUCTURAL MATERIALS (II) Horizontal structural elements <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <tbody> <tr><td>1st floor⁽²⁰⁾</td><td>☐ yes ☐ no</td></tr> <tr><td>2nd floor⁽²⁰⁾</td><td>☐ yes ☐ no</td></tr> <tr><td>3rd floor⁽²⁰⁾</td><td>☐ yes ☐ no</td></tr> <tr><td>Roof⁽²⁰⁾</td><td>☐ yes ☐ no</td></tr> </tbody> </table> (wooden, masonry vaults, composite steel and masonry, concrete) Roof typology⁽²¹⁾ ☐ Thrusting ☐ Low thrusting ☐ No thrusting 			1st floor ⁽²⁰⁾	☐ yes ☐ no	2nd floor ⁽²⁰⁾	☐ yes ☐ no	3rd floor ⁽²⁰⁾	☐ yes ☐ no	Roof ⁽²⁰⁾	☐ yes ☐ no																												
1st floor ⁽²⁰⁾	☐ yes ☐ no																																					
2nd floor ⁽²⁰⁾	☐ yes ☐ no																																					
3rd floor ⁽²⁰⁾	☐ yes ☐ no																																					
Roof ⁽²⁰⁾	☐ yes ☐ no																																					
OTHER FEATURES Finishing⁽²²⁾ Non structural elements⁽²³⁾ Strengthening elements⁽²⁴⁾																																						
NOTES																																						

Figure 4.5: Example of field datasheet survey developed by Giuliani [2020].

4.5 Application to Atlixco, Puebla.

Following the analysis provided in the previous section, the present section discusses the suitability of the Façade Vulnerability Index Approach for estimating damage grades in a set of constructions based on written and photographic documentation. This exercise is intended to evaluate the possibility of using this information, which is already available in the INAH datasheet, to input the seismic vulnerability assessment approach and estimate potential damages in existing building stocks whose seismic vulnerability is unknown. The case of study will be the city of Atlixco, Puebla, in the context of the $M_w = 7.1$ earthquake of the 19th of September, 2017 [Galvis et al., 2017]. This event has provoked serious damages in multiple settlements throughout the country, namely in the states of Puebla, Morelos, Oaxaca, Guerrero and Mexico City. Atlixco was selected as a case study due to its relative proximity to the epicentre (ca. 40 km) and the existence of a vast corpus of catalogued historical monuments. Furthermore, Atlixco is one of the legally recognised Zones of Historical Monuments (Zona de Monumentos Históricas), a designation provided by the INAH to settlements and regions with relevant densities and conservation of historical monuments [Presidencia de la República, 1990]. Besides, most of the respective catalogue sheets have recently been updated in 2015.

4.5.1 Vulnerability and damage estimation.

One of the most significant interests of the seismic vulnerability assessment methods reviewed is that they can be used to estimate damages, either to individual buildings or large building stocks, with a very low computation cost. In the specific case of the Façade Vulnerability Index approach, this damage estimation can be made by resorting to Eq. (4.3), which correlates a mean damage grade, D , with a vulnerability value, V , for a given macroseismic intensity, I_{EMS-98} [Musson et al., 2010]. Given this expression's empirical nature, the correspondence between the vulnerability index and the mean damage grade can be locally calibrated based on damage evidence, when available. Besides the seismic intensity, the model includes the vulnerability value and the ductility factor. The vulnerability value, V , can be related to the vulnerability index value, I_{vf} , by using Eq. (4.4). Finally, a ductility factor, Q , also plays a part in the equation. Ranging between 1 and 4, this value aims to take into account the ductility of the building, see Ferreira et al. [2014].

$$\mu_D = 2.51 + 2.5 \times \tanh \left[\frac{I_{EMS-98} + 5.25V - 11.6}{Q} \right] \quad (4.3)$$

$$V = 0.592 + 0.0057 \times I_{vf} \quad (4.4)$$

As discussed by Aguado et al. [2018], the mean damage grades obtained with Eq. (4.3) can be further related with a series of discrete damage grades, D_k , defined in the EMS-98 [Musson et al., 2010], whose understanding and interpretation are simpler and more straightforward. To do such a correlation, it is necessary to resort to Eq. (4.5), which establishes the analytical relationship between mean damage and discrete damage grade values based on a set of damage factors, DF , representing the cost of returning a building to its original undamaged condition. In agreement with Aguado et al. [2018], the damage factors adopted in this work are those proposed by Bramerini et al. [1995], which led to the results provided in Table 4.4.

$$\mu_D = 4 \times DF^{0.45} \quad (4.5)$$

Discrete damage grades, D_k	Damage factors DF	Mean damage grades μ_D
D_0 —No damage. No observed damage	0.00	[0.00, 0.50]
D_1 —Slight damage. Presence of very localised and hairline cracking	0.00	[0.50, 1.42]
D_2 —Moderate damage. Cracking around openings; localised detachment of wall coverings (plaster, tiles, etc.)	0.00	[1.42, 2.50]
D_3 —Severe damage. Opening of large diagonal cracks; significant cracking of parapets; masonry walls may exhibit visible separation from diaphragms; generalised plaster detachment	0.00	[2.50, 3.50]
D_4 —Very severe damage. Façade walls with large areas of openings have suffered extensive cracking. Partial collapse of the façade (shear cracking, disaggregation, etc.)	0.00	[3.50, 4.00]
D_5 —Destruction. Total in-plane or out-of-plane failure of the façade wall	0.00	[4.00, 5.00]

Table 4.4: Correlation between discrete damage grades and ranges of mean damage grade. Adapted from Aguado et al. [2018].

Two remarks should be made before moving on to the presentation of the building data-set and the discussion of the results. The first one is that all the results presented in the following have been obtained for a macroseismic intensity value of 7.5. This value was obtained from the Modified Macroseismic Intensity (MMI) maps produced by the United States Geological Survey (USGS) after the earthquake of the 19th of September, 2017 [United States Geological Survey USGS, 2017]. Also in this regard, it should be noted that since MMI and EMS-98 are equivalent [Musson et al., 2010], the intensity value to be inputted in Eq. (4.3) could be obtained from the maps directly. The second one is that the ductility factor adopted herein

is based on the Complementary Technical Code for Seismic Design of the Building [Gobierno del Distrito Federal, 2017], which is widely used in Mexico as a national standard for constructions. According to this document, a ductility value $Q = 1.0$ should be adopted for unconfined or unreinforced masonry building typologies in Mexico, regardless of whether the masonry is composed of brick or natural stone units. It is pertinent to note that the use of this value is indicative and thus open to discussion, namely in the context of experimental data. However, and given the lack of more specific criteria in the regulations, this ductility value was taken conservatively as 1.0. Moreover, although the 2017 earthquake has damaged several other building typologies, this analysis is targeted explicitly to unreinforced masonry buildings. This decision to address this (and only this) typology is backed by the need to limit the scale variation among the samples as a means for reducing the uncertainty and the range of applicability of the vulnerability index method itself. Monumental and religious buildings were excluded from the analysis.

4.5.2 The building dataset.

This section includes a general presentation of the nine buildings—representative of the unreinforced masonry typology—that served as the object of study herein. As mentioned before, these buildings' seismic vulnerability has been assessed using information that is publicly available on the National Catalogue for Historical Monuments. The analysis has also been complemented with data from Google Maps. The level of damage suffered by the buildings after the 2017 Atlixco earthquake (from now on referred to as observed damage, d_k) was initially based on after-event imagery from Google Street View and pictures and videos recorded after the event. Table 4.5 includes a picture of each one of the analysed buildings, before and after the event, as well as its INAH catalogue number and level of observed damage, d_k .

The selection of the (nine) buildings obeyed two fundamental criteria: (i) the building is included in the National Catalogue for Historical Monuments; and (ii) it has been captured by Google Street View imagery, both before and after the 2017 earthquake. The public datasheets [Instituto Nacional de Antropología e Historia México. Coordinación Nacional de Monumentos Históricos, 2020] permit to have an overview of the buildings in terms of their chronology, distribution, original and present uses and even some historical details (see Table 4.6).

Even if the catalogue datasheets are rarely specific about the year of construction, they suggest a century of construction based on documental information (e.g., historic cartography) and/or stylistic attributes. Eight out of the nine selected buildings are from the 18th and 19th centuries. An exception is the sample I-21-00024, which corresponds to the Claustro de la Merced (Cloister of La Merced). This con-

ID	Damage observations	Pre-event picture	Post-event picture
I-21 00087	D_2 . Opening of some diagonal cracks. Cracking of masonry and localised plaster detachment.		
I-21 00083	D_3 . Opening of diagonal cracks. Cracking of masonry and localised plaster detachment. Cracking in parapets.		
I-21 00086	D_4 . The building presented severe damages and was demolished soon after the earthquake.		
I-21 00066	D_4 . The building partially collapsed.		
I-21 00024	D_5 . The building collapsed during the earthquake.		
I-21 00107	D_2 . Opening of some diagonal cracks. Cracking of masonry and localised plaster detachment.		
I-21 00079	D_4 . The building presented severe damages, including a partial collapse of the façade.		
I-21 00078	D_2 . Cracking of masonry and localised plaster detachment.		
I-21 00121	D_4 . The building presented severe damages and was demolished soon after the earthquake.		

Table 4.5: Set of selected buildings, their corresponding Catalogue number and pre and post-event picture.

ID	Housing	Plan distribution	Storeys	Century
I-21-00087	Housing	Corridor around patio	1	19th
I-21-00083	Commercial	Polygon	1	18th
I-21-00086	Housing	Corridor around patio	1	18th
I-21-00066	Housing	Corridor around patio	2	19th
I-21-00024	Commercial and housing	Corridor around patio	2	17th
I-21-00107	Housing	Corridor with side patio	1	19th
I-21-00079	Commercial and housing	Corridor around patio	2	18th
I-21-00078	Housing	Corridor around patio	2	19th
I-21-00121	Housing	Corridor around patio	2	18th

Table 4.6: Summary of attributes available in the public INAH datasheet.

struction is originally from the 17th century but was subsequently abandoned and occupied as collective housing during the 19th century, in the context of the secularisation of the Mexican State. Then, the building had a series of heterogeneous interventions and types of use, including commerce and housing during the 20th and 21st centuries. This antecedent would be relevant for explaining an eventual eccentricity on the analysis for this construction. Except for this building, the rest of the constructions are considered by the INAH as conceived for housing, even if some of them had mixed commercial and housing uses.

All the analysed constructions have a maximum of two storeys and are typologically similar in their plan distribution. In fact, seven out of the nine samples correspond to the traditional distribution of rooms aligned to corridors around a central patio. One more sample has a lateral patio, which is sometimes a consequence of a property's subdivision. Finally, sample I-21-00083 is described in its datasheet as a «polygonal» plan, which may correspond to an irregular orthogonal distribution of rooms with no patio.

4.5.3 Analysis and discussion of the results.

Before going into the comparison between the analytical and the observed damages, it is pertinent to provide an overall picture of each building's vulnerability results. As graphically presented in Figure 4.6, the nine buildings analysed present a relatively heterogeneous distribution of their vulnerability classes; except parameters FP13 and FP12, whose classes are roughly the same for all buildings.

For this case study, this is strongly related to typological constants as well as reglementary restrictions on the use of façades (e.g., the prohibition of the use of external equipment or attached elements). In global terms, the sample has a mean seismic vulnerability index value, $I_{vf, \text{mean}}$, of 45.12. The minimum value of vulnerability index was obtained for building I-21-00078, 21.11, and the maximum, 89.63, was obtained for building I-21-00024. The associated standard distribution, $\sigma_{I_{vf}}$, is 20.36.

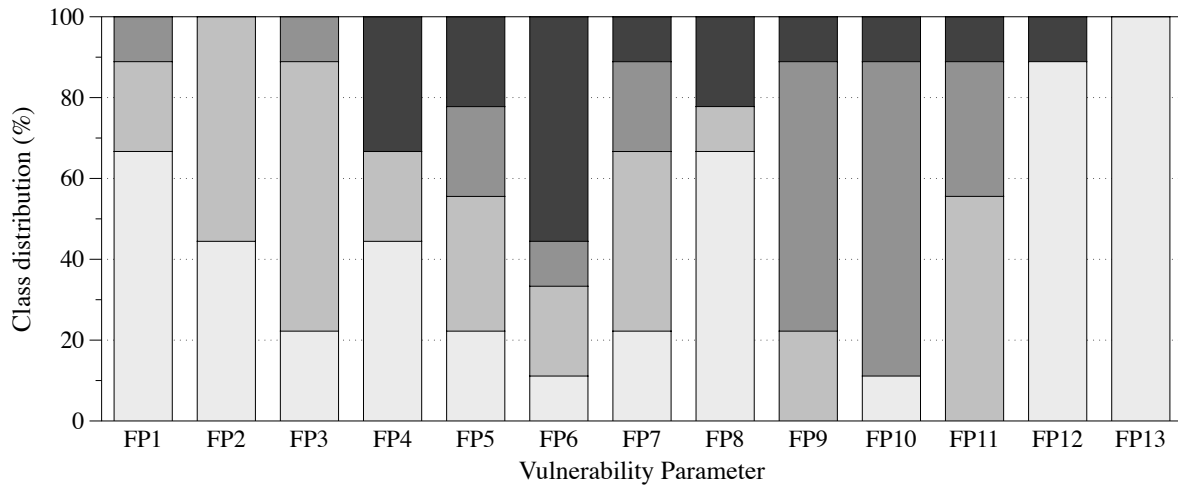


Figure 4.6: Vulnerability class distribution for the nine buildings evaluated.

Moving on to the analysis of the damages, whose values are also given in Table 4.7, it is interesting to see that the analytical, D_k , and the observed damages, d_k , exhibit a pretty good correspondence. As can be observed in Table 4.7, the predicted D_k was consistent with the observed d_k for all the nine buildings assessed. This good fitting does not exclude the need of calibrating the approach. In fact, the use of this method by departing from past calibrations is not intended to demonstrate the equivalence of the Mexican masonry typologies against those explored in the past, namely in Europe. Nevertheless, since the predicted damages are, in general, consistent with the observations, it is plausible to assume that the methodology can be accurately used to assess the seismic vulnerability of the constructions existing in the present case study, even with no further calibration. A relevant aspect of these results is that all the range between D_2 and D_5 was covered, which permits us to compare the representativeness for diverse levels of damage. Since buildings with no visible damage were excluded from the sampling, only values equal to or higher than D_2 are expected. The limitations found while grading some parameters are not neglectable. To verify the robustness and suitability of the results partially based on assumptions, it becomes necessary to assess how sensitive the results are if the assumed values change. In other words, it is necessary to carry a sensitivity analysis to verify if there are significant changes in the vulnerability and damage results.

4.5.4 Sensitivity analysis based on intervals.

The assumption of values for the analysis presented the previous section was based on typological similarities among the samples, accepting some informed judgements during the survey. Therefore, it is important to measure the grade of uncertainty that a given imprecise or inexact criterion may have in the overall scoring. Having this in mind, a proposal based on ranges has been carried, offering a set of

FP	Parameter	I-21-00087	I-21-00083	I-21-00086	I-21-00066	I-21-00024	I-21-00107	I-21-00079	I-21-00078	I-21-00121
1	Geometry of façade.	A(0)	A(0)	A(0)	A(0)	A(0)	A(0)	B(5)	B(5)	C(20)
2	Maximum slenderness.	A(0)	A(0)	A(0)	B(5)	B(5)	A(0)	B(5)	B(5)	B(5)
3	Area of openings.	A(0)	B(5)	A(0)	C(20)	B(5)	B(5)	B(5)	B(5)	B(5)
4	Misalignment of openings	A(0)	B(5)	D(50)	A(0)	D(50)	A(0)	D(50)	A(0)	B(5)
5	Interaction between cont. façades	C(20)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	C(20)	D(50)
6	Quality of materials	B(5)	C(20)	D(50)	D(50)	D(50)	B(5)	D(50)	B(5)	D(50)
7	State of conservation	B(5)	B(5)	C(20)	C(20)	D(50)	A(0)	B(5)	A(0)	D(50)
8	Flooring replacement	B(5)	A(0)	A(0)	D(50)	D(50)	A(0)	A(0)	A(0)	D(50)
9	Connection to orthogonal walls	C(20)	C(20)	C(20)	C(20)	D(50)	B(5)	C(20)	B(5)	B(5)
10	Connection to horizontal diaphragms	C(20)	C(20)	C(20)	C(20)	D(50)	C(20)	C(20)	A(0)	D(50)
11	Impulsive nature of roofing system	B(5)	B(5)	C(20)	C(20)	D(50)	B(5)	C(20)	B(5)	D(50)
12	Elements connected to the façade	A(0)	A(0)	A(0)	A(0)	D(50)	A(0)	A(0)	A(0)	C(20)
13	Improving elements	A(0)	A(0)	A(0)	A(0)	A(0)	A(0)	A(0)	A(0)	C(20)
I_{vf}	Normalised Vulnerability Index	27.59	33.70	54.44	54.44	89.63	22.96	51.11	21.11	51.11
μ_D	Damage grade	2.10	2.55	3.92	3.92	4.85	1.77	3.74	1.65	3.74
D_k	Analytical discrete damage	D_2	D_3	D_4	D_4	D_5	D_2	D_4	D_2	D_4
d_k	Observed discrete damage	d_2	d_3	d_4	d_4	d_5	d_2	d_4	d_2	d_4

Table 4.7: Summary of the vulnerability results.

results corresponding to two plausible extreme values for those attributes for which there is any degree of uncertainty. Instead of giving a closed value, this approach assumes the uncertainty associated with parameters FP6, FP8, FP9 and FP10, accepting that each attribute may be associated with an upper and a lower boundary that reasonably contains the actual value for each variable. For some samples and attributes, there are some grades with very low uncertainty (i.e., the lower and upper bounds remain the same). For others, that uncertainty may be more significant. For instance, sample I-21-00066 has a relatively low number of uncertainties compared to the sample I-21-00087 (Table 4.8), which may be reflected in a wider range for the vulnerability index values.

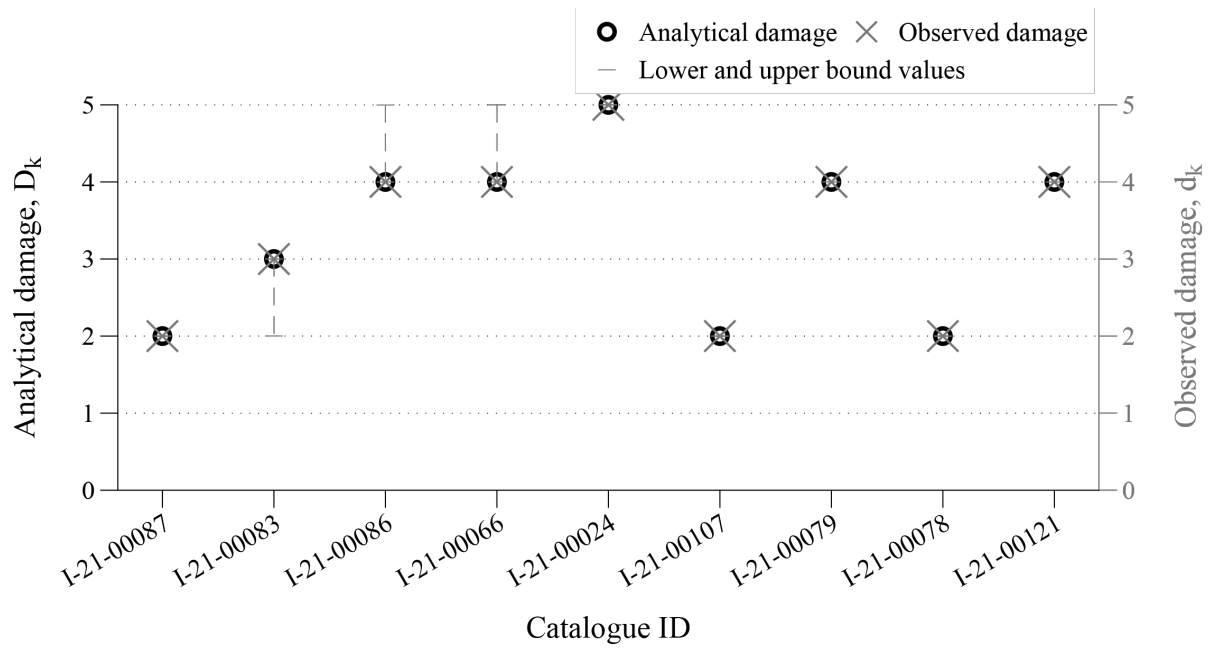
For six samples, the upper and lower estimated mean damage grades have the same value and have no differences regarding the observed damage and the estimated damage based on assumptions—see

FP	Parameter	I-21-00087	I-21-00083	I-21-00086	I-21-00066	I-21-00024	I-21-00107	I-21-00079	I-21-00078	I-21-00121
6	Assumed value	B(5)	C(20)	D(50)	D(50)	D(50)	B(5)	D(50)	B(5)	D(50)
	Lower bound	B(5)	D(50)	D(50)	D(50)	D(50)	C(20)	D(50)	C(20)	D(50)
	Upper bound	A(0)	C(20)	D(50)	D(50)	A(0)	A(0)	C(20)	A(0)	D(50)
	Interval (no. of grades)	2	2	1	1	4	3	2	3	1
8	Assumed value	B(5)	A(0)	A(0)	D(50)	D(50)	A(0)	A(0)	A(0)	D(50)
	Lower bound	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)
	Upper bound	A(0)	A(0)	C(20)	D(50)	B(5)	B(5)	C(20)	A(0)	C(20)
	Interval (no. of grades)	4	4	2	1	3	3	2	4	2
9	Assumed value	C(20)	C(20)	C(20)	C(20)	D(50)	B(5)	C(20)	B(5)	C(20)
	Lower bound	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)
	Upper bound	A(0)	B(5)	B(5)	C(20)	B(5)	B(5)	D(50)	B(5)	C(20)
	Interval (no. of grades)	4	3	3	2	3	3	1	3	2
10	Assumed value	C(20)	C(20)	C(20)	C(20)	D(50)	C(20)	C(20)	A(0)	C(20)
	Lower bound	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)	D(50)
	Upper bound	A(0)	B(5)	B(5)	C(20)	C(20)	C(20)	C(20)	B(5)	C(20)
	Interval (no. of grades)	4	3	3	2	2	2	2	3	2
	Total number of grades considered in the ranges of uncertainty	14	12	9	6	12	11	7	13	7

Table 4.8: Summary of the vulnerability results.

Table 4.9; Figure 4.7. Moreover, the lower and upper bounds obtained never exceed one grade, and the tendencies are still consistent with the observed damages, always containing the observed and estimated damage value. It is worth noting that, since the damage levels are actually a discrete representation for intervals (refer to Table 4.5), they may not appropriately adjust to the cases where the damage grades are close to the superior or inferior thresholds. Then, in addition to the discrete damage grades, it is also useful to compare the mean damage grade, μ_D . Such analysis permits to better appreciate the amplitude of the range offered in the results, as well.

In Fig. 4.8, it is possible to verify that there is consistency between the amplitude of the uncertainty, presented in Table 4.8, and the distance between the upper and lower values for the damage grade. It is relevant to observe that the suitability of using the discrete damage grades would be limited when working with intervals for grading the attributes instead of closed unique values, namely for those values that are close to the thresholds. The present approach also makes it possible to derive vulnerability curves based on «regions» (Fig. 4.9).

Figure 4.7: Ranges of values for analytical damage D_k and its comparison with the observed damage d_k .

		I-21-00087	I-21-00083	I-21-00086	I-21-00066	I-21-00024	I-21-00107	I-21-00079	I-21-00078	I-21-00121
I_{vf}	Based on assumptions	27.59	33.70	54.44	54.44	89.63	22.96	51.11	21.11	51.11
	lower bound	31.48	46.67	58.52	56.67	89.63	31.48	55.19	31.11	53.33
	upper bound	18.52	28.15	49.63	54.44	57.59	21.67	51.85	20.00	50.00
μ_D	Based on assumptions	2.10	2.55	3.92	3.92	4.85	1.77	3.74	1.65	3.74
	lower bound	2.39	3.47	4.11	4.03	4.85	2.39	3.95	2.36	3.86
	upper bound	1.48	2.14	3.65	3.92	4.07	1.68	3.78	1.57	3.67
D_k	Based on assumptions	D_2	D_3	D_4	D_4	D_5	D_2	D_4	D_2	D_4
	lower bound	D_2	D_3	D_5	D_5	D_5	D_2	D_4	D_2	D_4
	upper bound	D_2	D_2	D_4	D_4	D_5	D_2	D_4	D_2	D_4
d_k	Observed after 2017 Earthquakes	d_2	d_3	d_4	d_4	d_5	d_2	d_4	d_2	d_4

Table 4.9: Summary of the vulnerability results.

This kind of representation permits us to easily contextualise the tendency and amplitude of the variability for specific seismic intensity values. The overlap of the damage grades and the regions between the vulnerability functions are another expression of the consistency of both indicators. Once again, the regions may be more meaningful for understanding a field of vulnerability that intrinsically accepts uncertainties associated with the adequate grading of some attributes. This approach may be found valuable not only when it is impossible to have a comprehensive survey but also when the constructions' attributes

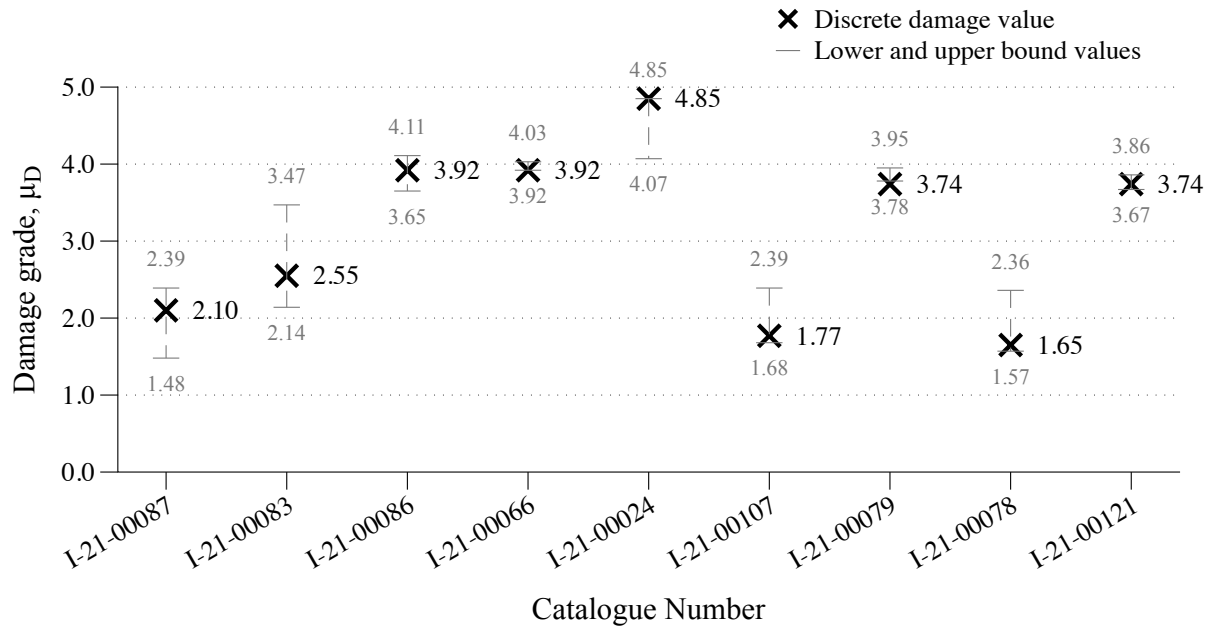


Figure 4.8: Plot of the μ_D values according to assumptions (discrete value) and the corresponding ranges.

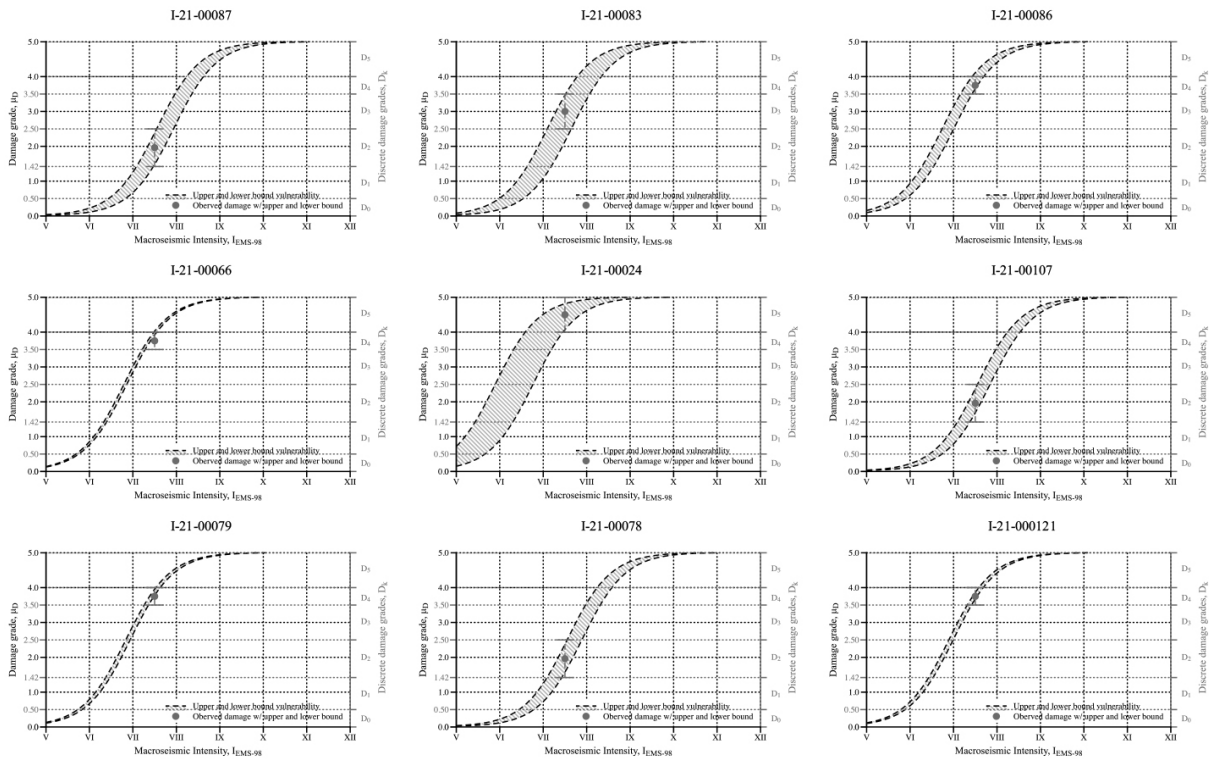


Figure 4.9: Vulnerability curves according to the boundaries of each one of the samples.

are close to the threshold between two contiguous grades. The use of these composed curves would also permit the development of subsequent works, such as the analysis of the nominal life of historical constructions (based on seismic return periods) and to analyse the impact, in terms of vulnerability, of certain interventions that would affect the Vulnerability Index Method attributes and qualification.

4.5.5 Limitations of the approach.

Even if the results suggest the validity of using this methodology, a series of limitations should not be forsaken. Firstly, because of its limited dimension, the sample used herein does not include all the possible attributes and damage levels. For this reason, it is not reasonable to see these results as definitive proof of reliability and accuracy. Another limitation is related to the application of the methodology itself, which, because it was performed in an indirect manner, encompasses some grade of uncertainty resulting from the assumptions made. In order to measure the impact of these two limitations, a simple validation procedure has been put into practice through: (1) comparing the information obtained following the procedure detailed in the previous sections with further sources of information, namely with a series of building catalogues developed by Martínez Bret [2018], Ruiz Herrera [2018], Tototzintle Huitle [2018] and Flores Rodríguez [2018]. These documents include the survey of most of the buildings of Atlixco in an early stage after the earthquake; and (2) an on-site survey of the buildings. Such a procedure allowed to confirm the suitability of the methodology presented in this work, since no inconsistencies were found between the information obtained from the National Catalogue for Historical Monuments and that obtained with more detailed, but not always available, sources of information.

Another relevant and expectable limitation of the procedure results from the fact that Atlixco's buildings do not belong to the same typology of masonry construction to which the vulnerability index method was initially designed for. Hence, some attributes do not accurately represent similar typological aspects, such as the geometry of the ceilings, for example. According to the results, this issue may be a minor limitation, but it definitively encourages enhancing and adapting the method in further research.

4.6 Final remarks.

The existing Mexican National Catalogue for Historical Monuments represents a valuable source of information regarding the historical buildings considered as monuments by definition of the law. The nature and type of some of the catalogue fields are compatible with some recent approaches for assessing the seismic vulnerability of constructions, which is relevant in the context of a country with frequent seismic activity. The Vulnerability Index Method allows assessing the seismic vulnerability of a building on the basis of a set of parameters, which are weighted according to their role for the global seismic performance of the buildings. Because the method is based on a relatively fast and simple set of observations, it seems pertinent to analyse the possibility of using the vast amount of data in the current version of the National Catalogue of Monuments to feed it. The present chapter is specifically dedicated to that analysis.

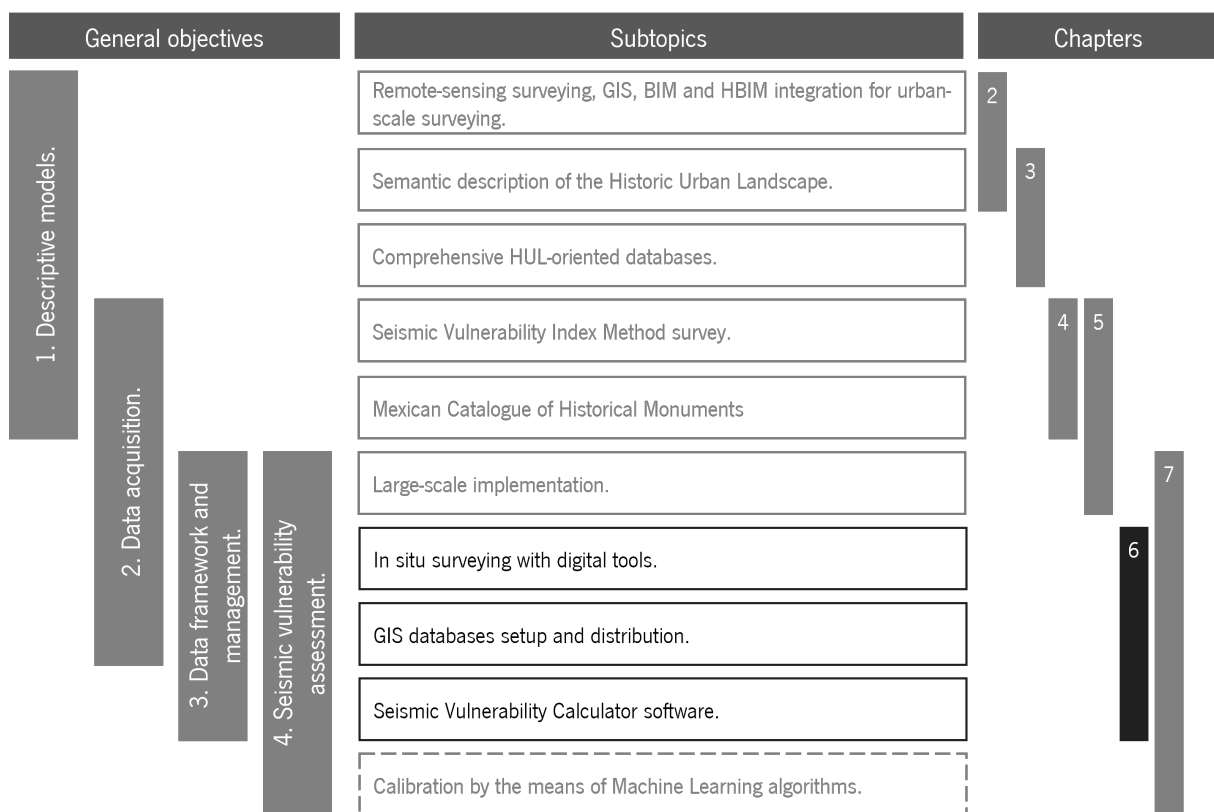
The comparison between the fields that compose the National Catalogue data datasheet and the ones of the Vulnerability Index Method proves the feasibility of integrating the vulnerability-oriented fields in the existing survey datasheet. Furthermore, previous works found in the literature demonstrate the feasibility of adapting the Vulnerability Index Method and its variation for façades to provide a coherent workflow that involves Mexican normative related to seismic characterisation, typological properties of materials and structures, etc. The existing adaptations found in the literature also suggest the robustness of the general theoretical base of the approach and allows for the identification of the parameters to be calibrated. The information related to the damages and losses during the 2017 earthquakes would be a valuable source of information for calibrating the vulnerability curves to some Mexican contexts and typologies.

The analysis applied to Atlixco, Puebla, demonstrated an encouraging scenario of suitability. The fitting of the observed and estimated damages does not necessarily imply that the methodology is ready to be extensively used with no changes. However, the results suggest that the existing approach could be adapted with minor calibrations. A more comprehensive sample would permit to carry sensitivity analysis to identify which parameters are more critical for explaining the behaviour of a determined typology of constructions. Besides, the analysis in a broader sample would permit defining the first insights for adapting the method to the most frequent features of Mexican building typologies; an adaptation of the method would imply not only a numerical calibration but also the adjustment of the descriptors to match the construction traditions of the country better. The logic of grading and classifying the building attributes are compatible with the idea of carrying out a typological classification based on specific features. Furthermore, it becomes necessary to contextualise the mechanical properties of the materials and structures for obtaining more accurate assessments.

An inherent condition for analysing vast samples is the capacity of performing large-scale data acquisition and management campaigns. The present experience revealed that the complementary and interdisciplinary use of diverse sources –such as the information contained in the National Catalogue for Historical Monuments, different scholar documents and on-site surveying—permit to get comprehensive descriptions for seismic vulnerability analysis purposes. A suitable workflow of acquisition, storage and management would favour the implementation of this approach. The major difficulties and limitations underlying the characterisation of some attributes were overcome by the adoption of a range-based criterion, which permitted us to obtain reasonably conservative results. Even so, and despite the results presented herein are promising regarding the suitability of this methodology to support large-scale seismic vulnerability analysis, further investigation on the limitations and accuracy of the approach should be conducted resorting to larger datasets.

Chapter 5

Vulnerability assessment of Mexican HUL: suitability and uncertainty analysis.



Rafael Ramírez Eudave, Tiago M. Ferreira and Romeu Vicente (2022) Parameterbased seismic vulnerability assessment of Mexican historical buildings: Insights, suitability, and uncertainty treatment, *International Journal of Disaster Risk Reduction*, 74, 102909. DOI: 10.1016/j.ijdrr.2022.102909

Abstract

The seismic vulnerability assessment of large sets of constructions is meaningful for anticipating post-earthquake scenarios in the context of loss prevention and resilience. These activities must overcome several difficulties related to the size and heterogeneity of the building stock, becoming even more complex when addressed to historical and vernacular structures.

The analysis of post-earthquake data has permitted the design of vulnerability assessment methods based on the identification of parameters related to the geometrical, structural and material features that rule the seismic behaviour of different typologies. A dataset of information about the 2017 Earthquakes in Mexico is used to discuss the suitability of a pre-established seismic vulnerability index approach. The compatibility between this approach and the information contained in the National Catalogue of Historical Monuments is the departure point for estimating levels of damage, which are then compared with those recorded in 2017.

This implementation requires a series of adaptations and strategies, including the adjustment of the description of the parameters for the Mexican context and the development of a strategy for considering the uncertainty when the information is limited, offering an alternative more conservative output. Based on the results of the comparison between the levels of damage estimated using the vulnerability index approach adopted in this chapter and those recorded in the aftermath of the 2017 Earthquakes in Mexico, it is plausible to confirm that this approach can be used in future seismic vulnerability assessment works in this region, provided that the limitations identified and discussed here are considered.

5.1 Introduction.

The report on Economic Losses, Poverty and Disasters from 1998 and 2007 [United Nations Office for Disaster Risk Reduction, 2017] contextualises how earthquakes are the natural events with the highest ratio of deaths by occurrence worldwide. While earthquakes represent only 7.8% of natural disasters on the planet between 1998 and 2017, they are related to 56% of casualties related to natural events. Among the major categories of disasters, earthquake is the one that threatens human lives the most. It is relevant to recognise that most casualties and losses are related to a relatively small number of events with a high magnitude.

The Global Assessment Report on Disaster Risk Reduction Atlas [UNISDR - United Nations Office for Disaster Risk Reduction, 2017] presents a so-called Annual Average Loss, an average amount that each country could expect to lose every year due to natural events. This report estimates that Mexico has a range between 1,001 and 2,000 million USD of annual losses due to earthquakes, resulting from an unfortunate combination of a high rate of occurrence (namely related to a relevant source of seismic activity on the south coast of the country) and a significant socioeconomic vulnerability. Mexican building stock has also been shown highly vulnerable to moderate to high magnitude seismic events. Authors such as Caprano et al. [2018], for example, have estimated reparations costs between 2,000 and 4,500 million USD for the seismic events of 2017 only.

The damages of the 2017 earthquakes are reflected in almost 180,000 affected housing units, approximately 0.56% of the national housing building stock. This proportion, however, is much more significant when focused on the most affected states, such as Oaxaca (6.07%), Chiapas (4.71%) and Puebla (1.79%), which also present high grades of marginalisation. Some municipalities reached records of more than 40% of housing units affected by the seismic events. These states also concentrate a relevant proportion of housing units corresponding to vernacular and/or historical constructions. For example, the National Catalogue of Historical Monuments [INAH, 2019] mentions 2,804 historical monuments (i.e., constructions built before the year 1900) that are currently used as a house in the state of Oaxaca. Ancient housing units also represent more than half of historical monuments in Puebla and Chiapas' states (Table 5.1).

State	Historical monuments	Houses considered as historical monuments
Oaxaca	5587	2804
Chiapas	2304	1514
Puebla	11359	6463

Table 5.1: Number of historical monuments and housing units that are considered historical monuments in the states of Oaxaca, Chiapas and Puebla, according to INAH [2019].

This phenomenon corresponds to a pattern in which the built environment is still rich in vernacular expressions and traditional construction techniques, especially in historical cities. It is relevant to point out that the investment for attending non-residential historical monuments (namely churches) would exceed 600 million USD [Lindero, 2017], concentrated in states with a high level of marginalisation. In fact, more than 50% of the historical buildings damaged by the 2017 Earthquakes are located in the states of Puebla and Oaxaca [García et al., 2018].

Therefore, a large-scale assessment of the seismic vulnerability of constructions would permit adopting proactive actions to limit losses due to seismic events. Even if there is vast knowledge about seismic occurrences in the country, there is still a gap related to the large-scale seismic vulnerability assessment of buildings. More specifically, the protection of cultural heritage depends on the proactive identification of the vulnerable constructions for carrying strategic interventions, sometimes based on maintenance or minor actions.

This article will discuss and identify the components of seismic risk to highlight the relevance of performing large-scale seismic vulnerability assessment exercises towards the outline of effective risk mitigation strategies. It will be discussed how to analyse the seismic vulnerability of historical and/or vernacular constructions, specifically adobe and masonry structures (which are predominant in most of the country's regions). An existing methodology based on parameters will be presented. The inputs, processes and outputs will be discussed to assess the suitability of the method in the context of the Mexican typologies. An application of the method in buildings of the historical city of Atlixco, Puebla, will permit insight into the limitations and challenges of applying the methodology, given the availability of data for large sets of constructions. The comparison between the preliminary results of the method against the real damages observed after the Puebla 2017 earthquake will permit to feed a discussion about the sources of uncertainty, some potential strategies for dealing with it and a potential typological adaptation. These results will also be meaningful for carrying sensitivity analysis aimed at outlining some general axis for adapting the methodology to the Mexican context, allowing a potential large-scale assessment tool for Mexican historical centres.

5.2 Seismic risk assessment.

A vast number of concepts are empirically related to risk, namely because it is intrinsically associated with any activity or system. Sometimes this semantical divergence leads to misuses or confusions that difficult to characterise risk in certain contexts appropriately.

5.2.1 Definition of Risk.

A very generalised and wide description of risk may be found in the international standard ISO 31000, related to the principles and guidelines for risk management [ISO - International Organization for Standardization, 2009]. This document states that «risk» is the uncertainty of achieving objectives due to external factors and influences. Risks are able to be identified, analysed and assessed, permitting further treatment until they become acceptable. The management of risks is a necessary step for increasing the likelihood of achieving objectives, having an awareness of threatening sources. Furthermore, it has a key role in improving governance, establishing a basis for decision-making and planning to minimise losses. Even though the ISO 31000 introduces all these concepts in the context of «organisations», all of them apply to individuals and material assets as well. The definition of risk unfolds a series of aspects that can be understood as the «objectives» for risk analysis purposes, such as financial, health, safety or environmental goals. Risk is characterised by referring to the potential events and consequences, combining the potential consequences with the likelihood of occurrence of the events. When addressed for seismic events, they can be contextualised according to the standard, as shown in Table 5.2, in which the concepts found in the ISO 31000 standard are applied to the effects that a seismic event of a determined magnitude would have in historical constructions.

Concept	Definition according to ISO 31000	In the context of seismic risk
Risk	Effect of uncertainty on objectives	Uncertainty on sustaining the structural performance of constructions (objective), i.e., damage or failure of the structures
Risk evaluation	Process of comparing the results of the risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable	Comparison of the expected damages for a determined seismic magnitude to assessing how tolerable is
Risk criteria	Terms of reference against which the significance of a risk is evaluated	The threshold for determining the acceptability of structural damage and/or loss of functions on the constructions
Risk source	Element which alone or in combination has the intrinsic potential to give rise to the risk	Geological, volcanic or other sources of earthquakes
Event	Occurrence or change of a particular set of circumstances	Dynamic excitation of the structures as a result of a seismic event
Consequence	The outcome of an event affecting objectives	Post-event scenario in terms of damages (fragility curve)
Likelihood	Chance of something happening	Function of return periods for a determined seismic intensity

Table 5.2: Concepts as defined in the ISO 31000 and contextualised for assessing the risk of an earthquake.

In the context of the ISO 31000 standard, the evaluation of the seismic risk of historical constructions can be based on the uncertainty of sustaining the performance conditions of a building (structural safety and/or functions) when it is subjected to dynamic loads. It is worth mentioning that the occurrence of a seismic event of a determined intensity, the level of damage, and the economic and human losses can all be represented by probabilistic functions. However, in this work, the goal is to get fragility curves that correlate the probability of different damage states being reached or exceeded for certain seismic intensities. Therefore, given the vulnerability level of the constructions, a probabilistic function for a seismic event (i.e., characterised by its intensity) would describe an approximated level of damage and loss, facilitating the adoption of risk criteria.

According to the Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas CENAPRED [2006] of the Mexican National Centre for Prevention of Disasters (CENAPRED), disasters are the consequence of the presence of a risk condition, related to a perturbation over an exposed asset. Furthermore, the risk associated with disasters involves the probability of loss and depends on the vulnerability and threats.

Therefore, CENAPRED encourages the development of the characterisation and quantification of the threats and the grade of vulnerability as a primary action for effectively mitigating the effects of threatening events. This guide generically considers the vulnerability as a function involving the intensity of the phenomenon (such as the intensity or the spectral acceleration when addressed to earthquakes) and the probability of damage and/or loss in a determined asset, including the extended impact that it may have. This damage estimative depends on the system and can be quantified based on several indicators, such as social or economic. However, any vulnerability analysis must classify and determine the exposed systems (i.e., must be based on a characterisation), establish thresholds for assessing the damages or losses, and, finally, express the potential scenarios for the exposed assets (Table 5.3).

Concept	Definition according to CENAPRED
Vulnerability	It is a function that involves the intensity of the phenomenon and the expected consequences on a determined asset.
Consequences	Damages and/or losses. It can express the wide impact that the damage or loss would have according to the interruption of functions that the asset represents, e.g., a hospital.
Failure modes	Total failure (collapse) of structure and/or foundations; damages on structural elements (walls and diaphragms); damages on non-structural elements (windows, finishing materials); damages on equipment and mobile assets.

Table 5.3: Key concepts according to the Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas.

Despite the popularity of the classical definition of risk as a measure of the probability and severity of adverse effects or the triad $\text{Risk} = \text{Threat} \times \text{Vulnerability} \times \text{Consequence}$, Haines [2009] identify risk as a vector with the units of the consequences. It is given as a function of time, the probability of the threat (initiating event), the probability of the consequences (given the threat), the state of the system (e.g., its vulnerability) and the resulting consequences. For example, in the context of seismic risk, the risk would be able to be understood as a vector in the units of damage or losses.

Risk definition always needs the identification of the vulnerability of the systems and elements exposed to a given threat. Since no successful risk evaluation, mitigation or control can be carried out without the analysis and characterisation of the vulnerability, suitable approaches for framing the specific vulnerability of elements towards the studied phenomena must be designed and put in place. Just as for risk, the concept of vulnerability needs to be clearly defined in order to contextualise it in a determined analysis.

5.2.2 Definition of vulnerability.

The concept of vulnerability has a broad utilisation throughout multiple and variate disciplines, namely to refer to a certain capacity for coping with change. The conceptual analysis of Brooks [2003] express that, in general, vulnerability is measured through outcome indicators, i.e., expectable losses and/or damages.

This analysis also gathers some definitions of vulnerability, emphasizing that of the International Panel on Climate Change: «The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and adaptive capacity».

In the same line, Luca and Verderame [2016] defines seismic vulnerability as «... the degree of loss to a given element at risk (e.g., buildings) resulting from the occurrence of an earthquake event». The definition offered by Gavarini [2001] is even more specific since it is framed on the structural performance of constructions in historical centres: «...the seismic vulnerability of a building is a quantity associated with its 'weakness' in front of earthquakes of a given intensity so that the value of this quantity and the knowledge of seismic hazard allow to evaluate the expected damages from future earthquakes».

This causal relation is highlighted by Vicente et al. [2005]: «Seismic vulnerability is an intrinsic property of the building structure, a characteristic of its own behaviour to seismic action described by a cause-effect relationship, in which the earthquake is the cause, and the effect is the damage suffered».

5.2.3 Vulnerability in the context of urban scale: challenges and previous experiences.

The measurement of the ability of the structures to cope with the demands imposed by earthquakes has to overcome, however, numerous challenges, such as the existence of great volumes of constructions on historical centres, the variety and complexity of structures (namely remarkable dissimilarities in materials and geometry), and the relations that exist between the constructions. In the most favourable but rare cases, common characteristics in a buildings sample are limited to a certain set of materials and relatively homogeneous structural systems [Oliveira, 2003]. According to Cocco et al. [2019], a feasible approach is to analyse large stocks of buildings in order to include the structural parameters that characterise the response of the buildings and involve the parameters' variability. This approach is limited by the effort required to comprehensively investigate and model a large number of samples, which encourages the use of simplified procedures.

The universe of historical buildings is hardly generalisable by any common characteristic (excepting, maybe, the antiquity), but there is a series of major groups that permit to group relevant sets of constructions in determined contexts. When analysing sets of historical buildings in the context of urban centres, it is possible to find some typological similarities that frame most constructions with a certain grade of variability, such as repetitive patterns for structural systems, geometric constants, etc. It is expectable to find a certain typological consistency in historical centres since architecture is namely a consequence of the local availability of resources (workforce, materials, technology), environmental conditions and cultural determinants.

For the above-exposed reasons, the typological approach is very helpful for taking advantage of the similarities among a certain set of constructions (e.g., by analysing similarities that also determine the structural response towards an earthquake) while the typological deviations of each sample permit to individualise and characterise it. In other words, typological approaches permit framing some determinants in the context of the seismic performance of constructions by maintaining the individual-scale analysis of the buildings. Even if the characterisation's uncertainty is still a challenge when performing typological analysis, an adequate definition of the fields to be characterised permits controlling and contextualising the uncertainty. Some sources of typological variety are listed by Valluzzi [2007] and include: type of masonry (e.g., regular brick or rubble stone), characterization of the properties of the materials (units and mortar, masonry as composite), knowledge of their mutual aggregation (in both thickness and façade), and the efficiency of connections among structural components (walls, floors, roof). Most of these characteristics

can be parametrised (i.e., to be described based on parameters such as intervals or thresholds) and classified. Furthermore, it is possible to identify sets of characteristics that are determinant for explaining or conditioning the performance or behaviour of a building in fields such as habitability, energetical efficiency or, for instance, seismic behaviour.

Parameter-based seismic vulnerability methods have been widely used worldwide, particularly in countries and regions where seismic activity is more significant or recurring, such as Italy, Greece or Nepal. The Gorkha earthquake (2015), one of the most destructive earthquakes of the recent past, is an outstanding example of a seismic event that has been intensively studied to consolidate and create new knowledge on the seismic vulnerability of various buildings typologies; often resorting to parameter-based vulnerability assessment methods. For example, Gautam et al. [2020] analysed more than 3000 schools by defining a series of structural and material parameters that were subsequently scored to obtain vulnerability classes. This work shows the suitability of typological classifications for designing robust descriptions beyond some typical taxonomical descriptions purely based on materials.

5.3 Seismic vulnerability assessment based on parameters for the Mexican context.

The identification and parametrisation of meaningful typological similarities among constructions are indeed based on many of the simplified approaches and methodologies that have been proposed over recent years to assess the seismic vulnerability of existing structures. Some simplified parameter-based methods have presented models for establishing vulnerability functions among specific typologies of constructions, such as the proposal of the National Centre for Prevention of Disasters (CENAPRED) and the so-called Vulnerability Index Method.

5.3.1 Qualitative assessment of the vulnerability of housing units towards seismic actions (CENAPRED).

The Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas [CENAPRED, 2006] offers a strategy for assessing the seismic vulnerability of housing units. However, this method is based on five levels of seismic vulnerability only, which constitutes a clear limitation – making it hardly usable as a tool to identify and prioritise intervention needs, for example. In Chapter 1.4, «Simplified criteria for qualitatively assessing the vulnerability of housing units towards seismic actions», this document includes

a simplified methodology based on a set of concepts related to the materiality of the constructions, the grade of social vulnerability, and the macroseismic region in which a determined municipality is located. Values. The criteria behind these concepts are summarised in Table 5.4.

However, the housing characterisation does not distinguish any details related to the construction system and/or the properties that may condition the seismic performance of the building. The word «masonry» is used in a generic way for any kind of stones, ceramic or cement blocks; plus, there is a poor specification for roofing systems. This methodology discusses (but does not involve) the suitability of a more comprehensive typological classification of the constructions. Another relevant limitation can be found in the microseismical zones (Figure 5.1). Even if the spectral accelerations of different soil types are considered, this approach does not permit obtaining intensity-based functions for damage, such as damage curves. This limitation is meaningful for developing vulnerability assessments based on different periods of return, restricting some approaches, such as the analysis that considers the constructions' nominal life.

Concept	Criteria and grading
Vulnerability Index $I_{RF} = I_{vf} \left(0.8 + \frac{I_M}{25} \right)$ *The gap between 0.5 and 0.6 seems to be a typographic error of the Guide.	The result of I_{RF} relates to five so-called “risk levels”: $\leq 0.0 \leq I_{RF} < 0.2$ – Very low risk $\leq 0.2 \leq I_{RF} < 0.4$ – Low risk $\leq 0.4 \leq I_{RF} < 0.5$ – Medium risk* $\leq 0.6 \leq I_{RF} < 0.8$ – High risk* $\leq 0.8 \leq I_{RF} \leq 1.0$
I_M , grade of social vulnerability towards disasters, from the municipal classification of the National Institute for Statistics, Geography and Informatics (INEGI).	$I_M = 1$ for very low $I_M = 2$ for low $I_M = 3$ for medium $I_M = 4$ for high $I_M = 5$ for very high
Physical vulnerability $I_{vf} = \frac{V_i P_i}{V_p P_m}$	V_i is the grade of the housing unit according to their materials V_p is the housing with the worst performance based on the criteria of V_i P_i is the level of seismic exposure in the region of study P_m is the maximum possible level of exposure
V_i , According to the materials of the structure	$V_i = 1$ for masonry walls with rigid roofing system $V_i = 2$ for masonry walls with flexible roofing system $V_i = 3$ for adobe walls with rigid roofing system $V_i = 4$ for adobe walls with flexible roofing system $V_i = 5$ for walls of weak materials with flexible roofing system
V_p	V_p is the maximum possible value for exposure. Therefore, $V_p = 5$

Table 5.4: Components for the qualitative assessment of the vulnerability of housing units towards seismic actions.

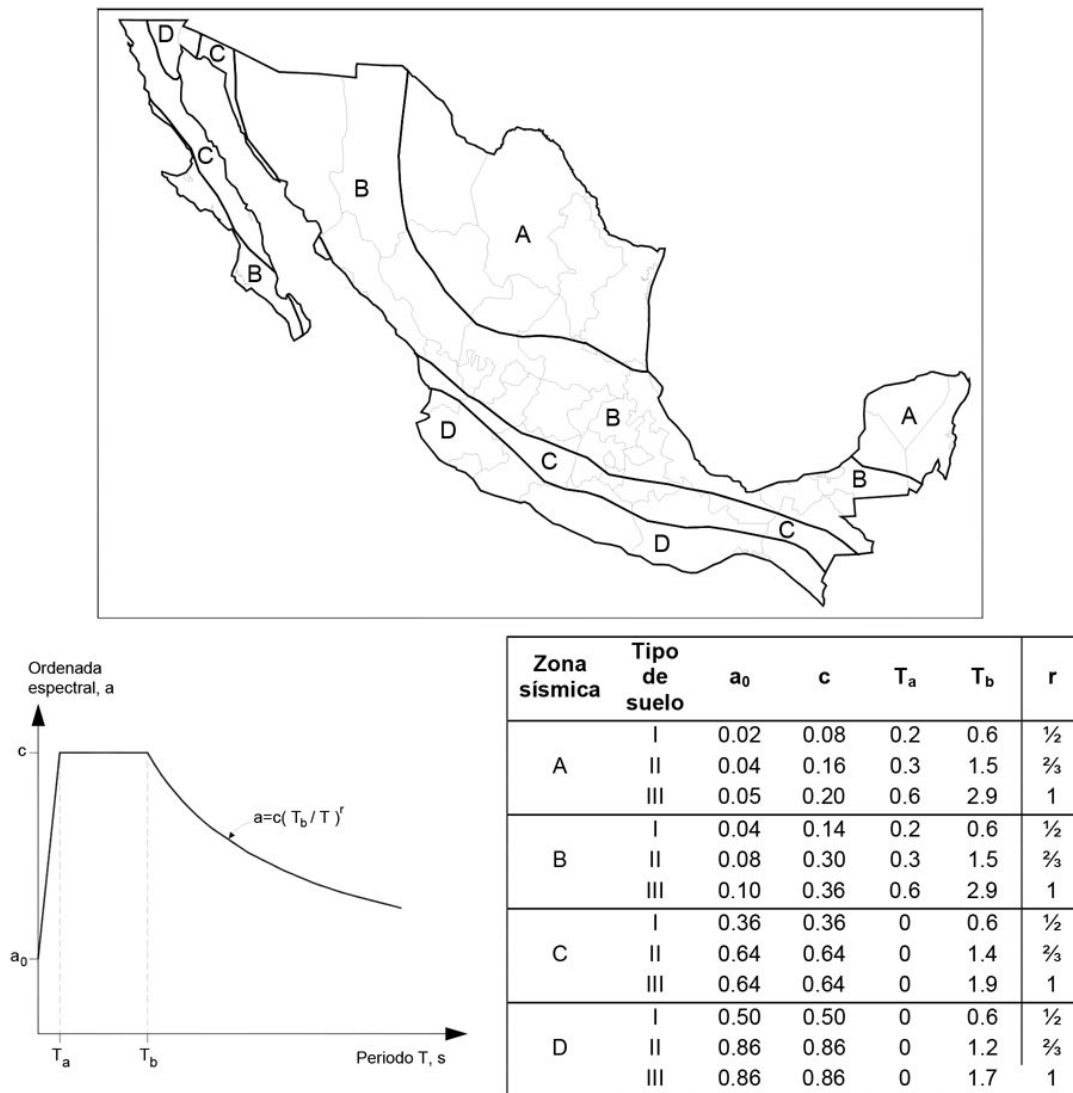


Figure 5.1: Seismic zones according to the Centro Nacional de Prevención de Desastres [Centro Nacional de Prevención de Desastres, 2006].

Even though the enhancement of the CENAPRED approach is beyond the scope of the present work, it is pertinent to recognise some positive experiences for enriching local approaches by using complementary tools. For example, Azizi-Bondarabadi et al. [2016] depart from an Iranian local parameter-based vulnerability assessment framework, discussing its capabilities and concluding its admissibility. The authors propose the addition of a complementary approach, the GNDT II method, for overcoming some of the limitations found in the original approach, namely those related to the absence of vulnerability curves, then proposing new damage factors specifically calibrated for the study area (associating local damage/cost ratios) and finally coming out with a set of fragility curves to three structural typologies identified among the school buildings. This work demonstrates the feasibility of enriching the Iranian-method index by linking it to a more complex method, which may be adopted in a similar way in the Mexican context.

5.3.2 The Vulnerability Index Method.

The physical damage and loss after a seismic event constitute a very valuable source of information for understanding the behaviour of the structures. This has improved the knowledge on the traditional building technology, antiseismic empirical or semi-empirical design techniques, the success and failure of building interventions and retrofitting techniques and more recently as valuable data for scientific approaches. The analysis of wide sets of data has allowed correlating meaningful relations between the intensity of earthquakes, some specific characteristics of constructions and the damages they present after a seismic event. The nature of this regressive analysis has allowed identifying several geometrical and material properties that are critical of the seismic vulnerability of traditional masonry building stock, such as for the activation of out-of-plane mechanisms.

The Italian National Group for the Defence from Earthquakes (Gruppo Nazionale per la Difesa dai Terremoti – GNDT) analysed large sets of data related to the characteristics of constructions that were damaged or lost as the consequence of earthquakes. These analyses allowed identifying essential features that were lately consolidated in a straightforward datasheet [Benedetti and Petrini, 1984, Gruppo Nazionale per la Difesa dai Terremoti—GNDT, 1994]. This characterisation is based on a series of typological ranges that are common to several cities in Italy but also relatable to other countries across Europe due to the similar traditional construction technology. Despite the inherent difficulties for a generalised mechanical characterisation of masonry, some general assumptions can be made, such as assuming brittle response in tension, frictional response in shear and anisotropy [Roca et al., 2010]. Hence, it becomes possible to generalise some mechanisms and configurations as the basis for parameter-driven assessments.

The general approach of this method is to consider a set of geometrical and material parameters. Each parameter is then able to be associated with the most suitable of four possible classes (A, B, C and D) that encloses the variability of the parameter assessed. Each parameter is associated with a weight p_i , which represents how crucial/important the characteristic is ruling the seismic performance of the building. For each parameter, the weight is multiplied by the value of the class c_{vi} , and the weighted sum of all parameters lead to a global vulnerability index [Calvi et al., 2006], as shown in Equation (6.1). The original proposal considered eleven parameters, but successive adaptations increased that number up to fourteen parameters divided into four groups: structural building system, irregularities and interaction, flooring and roofing systems and conservation status and non-structural elements (see Table5.5).

$$I_{vf}^* = \sum_{i=1}^{14} c_{vi} p_i \quad (5.1)$$

Parameters	Class C_{vi}				Weight	Relative weight
	A	B	C	D	p_i	
Group 1 Structural building system						50/100
BP1. Type of the resisting system	0	5	20	50	2.50	
BP2. Quality of the resisting system	0	5	20	50	2.50	
BP3. Conventional strength	0	5	20	50	1.00	
BP4. Maximum distance between the walls	0	5	20	50	0.50	
BP5. Number of floors	0	5	20	50	0.50	
BP6. Location and soil condition	0	5	20	50	0.50	
Group 2 Irregularities and interaction						20/100
BP7. Aggregate position and interaction	0	5	20	50	1.50	
BP8. Plan configuration	0	5	20	50	0.50	
BP9. Height regularity	0	5	20	50	0.50	
BP10. Wall façade openings and alignment	0	5	20	50	0.50	
Group 3 Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	
BP12. Roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						12/100
BP13. Fragilities and conservation status	0	5	20	50	1.00	
BP14. Non-structural elements	0	5	20	50	0.75	

Table 5.5: Vulnerability Index parameters, according to the calibration of Ferreira et al. [2017c].

As schematised in Figure 5.2, in which the circumference has been proportionally divided according to the weight of each parameter, certain aspects of the construction are significantly more determinant than the rest, such as parameters BP1 and BP2. The concentric circles are also proportional to the numerical value according to the class. It is convenient to keep in mind that the progression between classes can be more significant between classes C and D. If the area of the entire circle is 650 units and the regions are shaded according to the grade of each parameter, then it graphically represents the true value of I_{vf}^* as a proportional shaded surface.

This method has been applied to numerous case studies, such as the ones of Coimbra [Vicente, 2008] [Aguado et al., 2018], Seixal [Ferreira et al., 2013], Horta [Ferreira et al., 2017c] and Leiria [Blyth et al., 2020], Portugal; Annaba, Algeria [Athmani et al., 2015]; Timisoara, Romania [Mosoarca et al., 2019]; Osijek, Croatia [Hadzima-Nyarko et al., 2016] etc., demonstrating the suitability of this approach to be adapted based on adjustments of the weights and damage curves according to the typological characteristics [Giuliani, 2020]. The concerns related to the constraints for accomplishing an extensive survey (e.g., not having complete access to the building site or drawings) encouraged the design of a complementary façade scale evaluation approach. This method is mostly focused on the potential assessment of out-of-plane mechanisms (by assessing building features that make them more prone to such) and was widely explored initially [Vicente, 2008], that proposed an initial set of 10 parameters that have been expanded

in the following years [Ferreira et al., 2014, 2017a, Aguado et al., 2018]. The logic and procedures behind this method are the same that those applied for the building scale method, considering a total of 13 parameters (see Table 5.6).

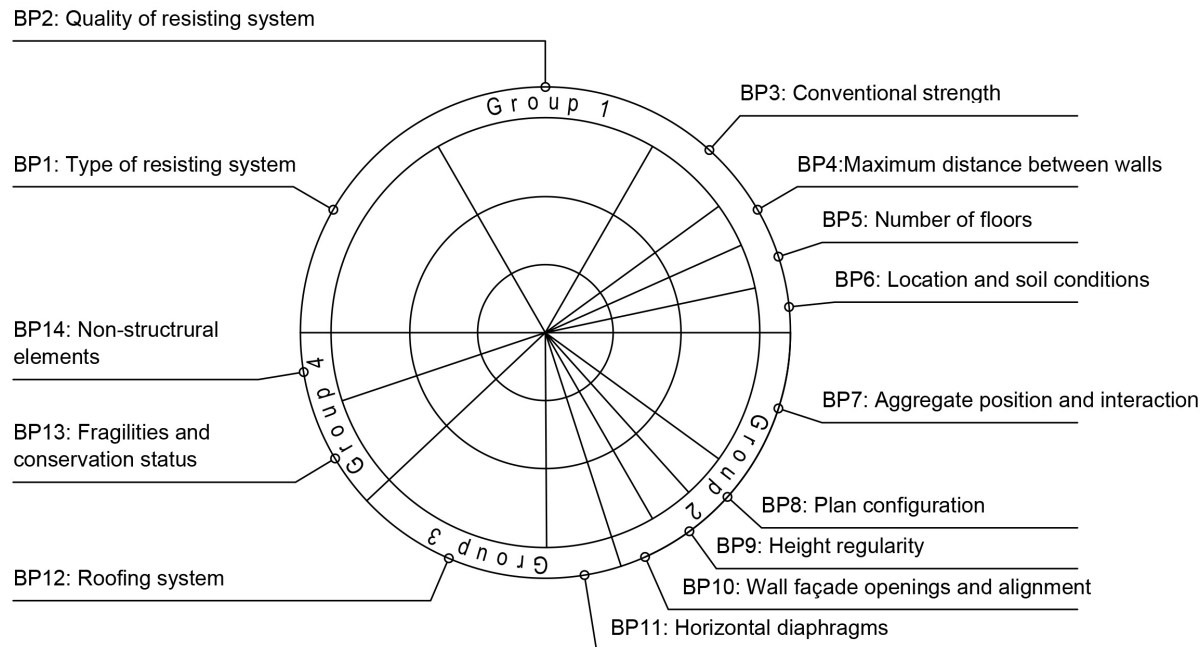


Figure 5.2: Schematic representation of the parameters and their weight.

Parameters	Class C_{vi}				Weight p_i	Relative weight
	A	B	C	D		
Group 1 Façade geometry, openings and interaction						16.7/100
FP1. Geometry of façade	0	5	20	50	0.50	
FP2. Maximum slenderness	0	5	20	50	0.50	
FP3. Area of openings	0	5	20	50	0.50	
FP4. Misalignment of openings	0	5	20	50	0.50	
FP5. Interaction between continuous façades	0	5	20	50	0.25	
Group 2 Masonry materials and conservation						31.5/100
FP6. Quality of materials	0	5	20	50	2.00	
FP7. State of conservation	0	5	20	50	2.00	
FP8. Replacement of original flooring system	0	5	20	50	0.25	
Group 3 Connection efficiency to other structural elements						33.3/100
FP9. Connection to orthogonal walls	0	5	20	50	2.00	
FP10. Connection to horizontal diaphragms	0	5	20	50	0.50	
FP11. Impulsive nature of the roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						18.5/100
FP12. Elements connected to the façade	0	5	20	50	0.50	
FP13. Improving elements	0	5	20	50	-2.00	

Table 5.6: Parameters and vulnerability classes, according to Aguado et al. Aguado et al. [2018].

Although the identification of the characteristics that critically determine the seismic vulnerability is very dependent on typological similarities, it is possible to admit a certain level of similarity among historical constructions in determined contexts. For example, Mexican housing constructions in historical centres are typologically related to the use of local materials and traditional construction techniques and solutions that are also common in European countries. The Viceroyalty of New Spain (1521-1821) represents a period in which a permanent exchange of architectonic and urban tendencies moulded the physiognomy of the historical cities in Mexico. These constructions have numerous similarities with their chronological counterparts in the Iberian Peninsula. This cultural bridge is a strong indication that this approach can be suitable to assess the historical constructions in the Mexican urban context.

A limitation, however, is that the criteria and analysis for the parameters are strongly focused on typological constants of the European constructions. This situation does not hinder the application to the Mexican building stock. However, the description and grading of all the parameters are needed in order to facilitate an objective framework for its application. The works of Salazar and Ferreira [2020] explored the assessment of buildings in the historical neighbourhood of La Merced in Mexico City by using the Vulnerability Index Method approach. This experience established a set of typologies (four geometrical types and nine material types) for generalising a set of 166 constructions (however, several limitations are implicitly present when assuming generalisations throughout a sample). This typological approach was potentially limited, for example, when there are morphological modifications due to building interventions (interior space changes, refurbishments, etc.). In this context, the analysis of individual buildings instead of groups is still a gap in literature addressed to Mexican assets.

It is worth highlighting that this approach has also been used as a conceptual basis for developing more specific methods, such as the Seismic Vulnerability Index for Vernacular Architecture (SVIVA), developed by Ortega et al. [2019]. The SVIVA formulation includes a definition of the parameter's vulnerability classes according to numerical reference models. The relative weight of each parameter was obtained using multiple linear regression and expert opinion. Although this approach was initially targeted at Portuguese vernacular architecture, the authors admit its applicability to similar structures outside the Portuguese context. In fact, it is plausible to assume that this approach would also be suitable to analyse the present case of study. The main reason for adopting here the Vulnerability Index Method proposed by Ferreira et al. [2017c] lies in the fact that the vulnerability parameters are more explicitly unfolded in this method. Despite that, the data generated in this work can likely be used to generate vulnerability results with the SVIVA approach, providing, therefore, a good base for future works of validation or numerical calibration based on the effects of the 2017 earthquakes in the Mexican constructions.

Data availability for single buildings is a very relevant challenge for applying the Vulnerability Index Method to large sets of constructions. However, the Mexican context provides an advantage due to the existence of the National Catalogue of Historical Monuments. Developed by the National Institute for Anthropology and History (Instituto Nacional de Antropología e Historia, INAH), this catalogue is a valuable resource that groups more than 100,000 datasheets that individually describe historical monuments in Mexican territory. Since Mexican law determines that any construction built before the year 1900 must be considered as a historical monument [Cámara de Diputados, 2012], this catalogue is wide.

The experiences of Ramírez Eudave and Ferreira [2021d] provided a first insight on the use of this catalogue for feeding the Vulnerability Index Approach, supporting its suitability by comparing the expected damages and the effects of the 19th of September, 2017 earthquakes in Atlixco, Puebla, that had a Modified Mercalli Intensity of 7.5 in this city [United States Geological Survey USGS, 2017]. This city is a representative case of a Mexican historical city centre, recognised as a Zone of Historical Monuments (Zona de Monumentos Históricos) by the INAH. This denomination is given due to a relevant concentration of historical monuments and provides a special framework for its safeguarding. Even if the proof-of-concept study was based on a limited set of nine constructions, it strongly suggests the suitability of the methodology for assessing Mexican constructions. Although the catalogue ideally covers almost all the parameters to be used by the Vulnerability Index Method, this experience also found a strong limitation since most of the datasheets is incomplete. A more extensive and comprehensive experience was possible in the scope of a series of surveys performed in the previous months before the 2017 earthquakes.

5.4 Materials and methods: the dataset.

A comprehensive catalogue for the historical monuments of the city of Atlixco, Puebla, following the model of the INAH datasheet, was used by Martínez Bret [2018], Ruíz Herrera [2018], Tototzintle Huitle [2018] and Flores Rodríguez [2018] and within the scope of their work an improved datasheet was made (see Figure 5.3) that contains additional and valuable information fields, such as general measurements and façade drawings (see Table 5.7). These works were mostly developed in the months that preceded the earthquakes of September of 2017, giving a valuable testimony of the general conservation state of the constructions in a pre-damage stage. Furthermore, some of the datasheets also include descriptions of the damages suffered because of the earthquakes. The use of this information allowed to significantly enlarges the first insight on the use of the Mexican Catalogue by applying the Vulnerability Index Method approach to a total of 83 constructions.

BENEMÉRITA UNIVERSIDAD AUTÓNOMA DE PUEBLA. FACULTAD DE ARQUITECTURA. MAESTRÍA EN ARQUITECTURA CON ESPECIALIDAD EN CONSERVACIÓN DEL PATRIMONIO EDIFICADO. FICHA DE CATALOGACIÓN DE BIENES INMUEBLES PARA ZONA DE MONUMENTOS HISTÓRICOS. ATLIXCO, PUEBLA.		Folio de Campo: 21-019-001 No. de Ficha: 4 Folio Único: SECH-4 Clave Geoespacial: 210190001063A006
1. LOCALIZACIÓN DEL INMUEBLE. Estado: Puebla Municipio: Atlixco Localidad: Atlixco Región geográfica: Región V Calle y Número: Libertad No. 202 Otra localización: Calle Libertad esquina 4 Ote Colonia o Barrio: Centro Georreferencia: 20°51' 0.36"N 14°55' 96.67"E	6. CROQUIS DE UBICACIÓN. 	7. PLANTA ARQUITECTÓNICA.
2. IDENTIFICACIÓN. Nombre del Inmueble: Casa Habitación Uso Original: Casa Habitación Uso Actual: Casa habitación y escuela Epoca de Construcción: S.XVI () S.XVII () S.XVIII () S.XIX (X) S.XX (X)	8. DESCRIPCIÓN DEL INMUEBLE. Fachada Principal: Antes desplantada sobre un rodapié hoy se encuentra lisa con cuatro vanos en la parte baja de los cuales tres corresponden a locales comerciales y uno al acceso principal que se enmarca por una plana banda conservando la puerta de madera, en la parte alta cuatro vanos de igual simetría con balcón de piedra y barandal de herrería rematados con un arco conopial y cierra el conjunto una cornisa y perfil moldurado con pequeñas perforaciones semicirculares. Fachada Lateral: Sobre la 4 ote de apariencia lisa con tres vanos simétricos que se repiten en lo alto, balcones de piedra y barandal de herrería con arco conopial. Remata con un perfil y cornisa similares a la fachada principal. Interior del Inmueble: Aunque ha sido modificado para albergar las aulas de la escuela actual, mantiene sus dimensiones en habitaciones, así como los dos patios; el central y uno trasero que es utilizado para servicio.	9. CARACTERÍSTICAS TIPOLOGICAS: El inmueble mantiene la distribución original a través del patio central que da acceso a las aulas, mismas dimensiones, aunque fachada modificada. Arquitectura del S. XIX. Se utiliza el concreto armado para el cambio en la fachada. Distribución de habitaciones que surge a partir de dos patios interconectados con los diferentes espacios. Los muros, como en otras épocas, continúan siendo mixtos con el empleo de piedra, adobe y tabique. Así como cantera en elementos como el piso y la escalera. En la actualidad ha sido modificado para albergar una escuela, motivo por el cual permanece conservado, sin embargo un falso histórico se creó al tapar la fachada original por una de concreto, misma que tras el sísmo de septiembre de 2017 se vino abajo dejando al descubierto la original. Sin embargo permanecerá oculta pues se volvió a levantar de concreto.
3. CARACTERÍSTICAS CONSTRUCTIVAS. Fachada Principal. Acabados: Adobe con aplomado Azul Muros. Materiales Predominantes: Piedra, adobe y tabique Anchaz: Roca Entrepisos: Viga, ladrillo Materiales Predominantes: Ladrillo Cubierta de Azotea. Materiales Predominantes: Viga y Ladrillo Forma de la cubierta: Plano Número de Niveles: 2 Otros Elementos: Escalera Estado de Conservación: Bueno	10. FACHADA. 	11. HISTORIA DEL INMUEBLE: «CASA HABITACIÓN: La fachada ha sufrido modificaciones en la parte baja ya que varios vanos han sido ampliados; construcción que data del siglo XIX, cuyos muros indican la posibilidad de una edificación anterior; es de dos niveles y cuenta con dos patios, en uno de ellos se conserva una hermosa escalera de piedra original.» Inscripción en placa del edificio
4. ASPECTOS LEGALES. Régimen de propiedad: Privado Propiedad Actual: Persona Física	12. RECOMENDACIONES DE INTERVENCIÓN: - Respetar el patrimonio histórico existente. - Respetar alturas que predominen en el patrimonio edificado. - Revisar propuestas de color en base a la paleta de colores del INAH para patrimonio edificado. - Consultar a especialistas para conocer los criterios mínimos en proyectos de intervención. - Todo lo que no es considerado como patrimonio histórico y artístico deberá integrarse de manera visual a los inmuebles reconocidos existentes.	11. CONTEXTO INMEDIATO.
5. ANÁLISIS DEL LARGUILLO. En estos contextos se observa por un lado que las alturas son uniformes, si embargo por el otro lado son discontinuas, debido en parte a la construcción de arquitectura contemporánea que está sobrepasando los límites de las construcciones existentes y resulta de entre todo el conjunto, pero también resulta el uso de diferentes materiales y sistemas constructivos en una misma calle.		

Figure 5.3: Example of a datasheet (in Spanish). Extracted from Flores Rodríguez 2019 Flores Rodríguez [2018].

5.4.1 Parameters and grading for Atlixco:building scale approach.

During the analysis of these datasheets, it was found that the descriptions of the parameters approach may need to be contextualised for adequately grading the vulnerability classes and fully describing the characteristics contained in the datasheets. A semantical and typological analysis was made in order to identify some potential sources of uncertainty or divergence between the Vulnerability Index Method and the structure and data given by the datasheet information, which is based on the original structure of the INAH database. Both approaches, the one for the building and the one for the façade, were analysed. The criteria followed and adopted for the building scale is from Vicente [2008]. A full description of the 13 parameters (BP_i), including a short discussion regarding the specific conditions that have been considered for dealing with the necessary adaption to apply these approaches, is given in Appendix B. A list of criteria for the façade approach proposed by (Vicente 2008) is also discussed and enriched with the considerations of Aguado [2017] for those parameters that were not considered in the previous versions of the approach.

Field	Content of the field	Field	Content of the field
F0	Key Building Code	F9	Legal aspects. Regime of property
F1	Site and Location: State, Municipality, Settlement, Region, Street and number, coordinates.	F10	Façades of the entire block front
F2	Identification. Name, original use, present use, the century of construction.	F11	Location (map). (Isolated, Corner, Row Building, End-row building)
F3	Construction characteristics of the main façade: Finishing/Coverings	F12	Architectonic plan (ground floor).
F4	Construction characteristics of the walls: Predominant materials and thickness.	F13	Drawings and photo rendering of the façades of the block.
F5	Construction characteristics of the floor diaphragms: Predominant materials.	F14	Description of the building.
F6	Construction characteristics of the roofing systems: Predominant materials, geometry.	F15	Interventions recommended.
F7	Number of floors	F16	Typological characteristics.
F8	State of conservation (Good; Regular; Poor).	F17	History of the building.

Table 5.7: Fields considered in the datasheets of Martínez Bret [2018], Ruíz Herrera [2018], Tototzintle Huitle [2018] and Flores Rodríguez [2018].

5.4.2 Comparison between observed and analytical damage grade obtained with the Vulnerability Index Method.

Once obtained a vulnerability index for the buildings, it is possible to estimate levels of damage for different intensity events. These damage functions involve some additional parameters, such as a ductility factor for the construction $Q = \{1 : 4\}$ and the macroseismic intensity in the IEMS-98 scale. These parameters, together with a normalised vulnerability value V (Eq. (6.2) and (6.3)), allow one to estimate a mean damage grade μ_D Blyth et al. [2020] that can range from 0 up to 5 (Eq. (6.4)), including a correction factor introduced when the seismic intensity is $I \leq 7$ (Eq. (6.5)). Previous experiences, such as the one of Aguado Aguado et al. [2018], have explored the qualitative correspondence existing between values for μ_D and the discrete damage grades D_k defined in the EMS-98 scale [Centre Européen de Géodynamique et de Séismologie, 1998], based on the macroscopic evidence of damage. This correlation also facilitates the inclusion of damage factors DF that represent the cost of repairing a construction (Eq. (5.6)). The damage factors herein adopted are those proposed by Bramerini et al. [1995]. The correspondences among mean damage grades, damage factors and discrete damage grades are shown in Table 5.8.

$$I_v = \frac{I_v^* \times 100}{750} \quad (5.2)$$

$$V = 0.592 + 0.0057 \times I_v \quad (5.3)$$

$$\mu_D = \left[2.5 + 3 \times \tanh \left(\frac{I_{EMS-98} + 6.25 \times V - 12.7}{Q} \right) \right] \times f(V, I); 0 \leq \mu_D \leq 5 \quad (5.4)$$

$$f(V, I) = \begin{cases} \frac{V}{e^{(2 \times I - 7)}} & \text{for } I \leq 7 \\ 1 & \text{for } I > 7 \end{cases} \quad (5.5)$$

$$\mu_D = 5 \times DF^{0.45} \quad (5.6)$$

Discrete damage grades, D_k	Damage factors, DF	Mean damage grades, μ_D
D_0 —No damage. No observed damage	0.00	[0.00, 0.50]
D_1 —Slight damage. Presence of very localised and hairline cracking	0.00	[0.50, 1.42]
D_2 —Moderate damage. Cracking around openings; localised detachment of wall coverings (plaster, tiles, etc.)	0.00	[1.42, 2.50]
D_3 —Severe damage. Opening of large diagonal cracks; significant cracking of parapets; masonry walls may exhibit visible separation from diaphragms; generalised plaster detachment	0.00	[2.50, 3.50]
D_4 —Very severe damage. Façade walls with large areas of openings have suffered extensive cracking. Partial collapse of the façade (shear cracking, disaggregation, etc.)	0.00	[3.50, 4.00]
D_5 —Destruction. Total in-plane or out-of-plane failure of the façade wall	0.00	[4.00, 5.00]

Table 5.8: Correlation between discrete damage grades and ranges of mean damage grade.

The macroseismic intensity estimated by the United States Geological Survey for the 19th of September 2017 earthquake in Atlixco Centre Européen de Géodynamique et de Séismologie [1998], reported with a value of 7.5 in the Modified Macroseismic Intensity (MMI) scale, is taken in this work. Plus, the equivalence of MMI and EMS-98 scales, discussed by Musson et al. [2010], has been assumed. The ductility factor for performing the assessment is that considered by the Complementary Technical Code for Seismic Design of the Building for Mexico City Gobierno del Distrito Federal [2017], that is often considered as a national

standard for seismic design. This code recommends adopting a ductility value of $Q=1.0$ for unreinforced masonry structures, regardless of whether the masonry is composed of brick or stone units. This is due to the lack of more specific criteria on the regulations and experimental data for this sample. This indicative value is conservative and can and should be discussed and adjusted when new evidence is available.

5.4.3 The role of uncertainties in the assessment process.

The use of the updated catalogue for Atlixco represents a privileged opportunity for performing a comprehensive assessment based on recent information. Nevertheless, there are some situations in which the information found in this source hinders being insufficient for accurately grading a determinate parameter. This situation can happen because of a series of situations, such as low-resolution figures (floorplans or photos), semantical divergence (on the use of unprecise descriptions of masonry works), subjective undefined observations, or lack of data. Therefore, an additional grading was introduced with the objective of assessing the reliability of the vulnerability class assigned to a determinate parameter.

This grading, named Quality Check (QC), was conceptualised for accomplishing two fundamental purposes. Firstly, it allows identifying which parameters were accurately assessed and which ones are based on relatively weak assumptions, favouring a straightforward enhancement of the database by addressing specific aspects of the survey. Secondly, it also allows assuming a more conservative approach towards the lack of information. Even in the cases where all the parameters in which the existing data was considered as insufficient were reasonably assessed by means of experience and engineering judgement, the QC grading facilitates the calculation of an alternative vulnerability index by accepting that certain parameters can receive a more unfavourable condition than the originally assumed. The QC grading considers four different levels of accuracy and quality of information, namely:

- QC0: High quality. Grade verified with a high level of certainty. Data is explicitly contained on the datasheets and have been verified in-situ or by more than two sources (e.g., press and/or Google Maps).
- QC1: Medium quality. Deduced from secondary sources, (photographs, drawings, testimonies, etc).
- QC2: Low quality. Reasonably based on typological similarities and hypothesis based on experience.
- QC3. Absence of information. The grade is merely indicative but still better than a random decision.

For this study, each construction received two sets of parameter grading. The first one corresponds to the grade assignment regardless of the QC level. The second one modifies this assessment according to the QC level if a parameter is associated with QC2 or QC3 levels. A specific parameter with a QC2 classification will receive a more conservative vulnerability class (i.e., from A to B, B to C or C to D), while QC3 will imply a two-level downgrade (i.e., from A to C and B to D). All the parameters with QC0, QC1

and those that cannot receive the corresponding downgrade (e.g., a parameter graded with D with a QC2) remain unchanged, as presented in Table 5.9.

Parameter	Original grade	QC	Action	Conservative grade
BP1	A	QC1	Remains the same	→ A
BP2	B	QC0	Remains the same	→ B
BP3	C	QC2	One-step downgrade, if possible	→ D
BP4	D	QC3	Two-step downgrade, if possible	→ D
BP5	B	QC1	Remains the same	→ B
BP6	C	QC2	One-step downgrade, if possible	→ D
BP7	D	QC1	Remains the same	→ D
BP8	B	QC0	Remains the same	→ B
BP9	A	QC3	Two-step downgrade, if possible	→ C
BP10	D	QC1	Remains the same	→ D
BP11	C	QC2	One-step downgrade, if possible	→ D
BP12	D	QC2	One-step downgrade, if possible	→ D
BP13	C	QC1	Remains the same	→ C
BP14	B	QC3	Two-step downgrade, if possible	→ D

Table 5.9: Example of conservative grades obtained after combining different grades and QC levels.

This approach has been found useful for expressing mean damage grades as a range instead of a nominal value. It is assumed that the interval between the original and conservative assessments (upper and lower bounds) reasonably cover the real conditions of the construction – the larger the uncertainty, the larger the interval for the mean damage grades, μ_D . This approach is considered feasible and suitable given that the observed damage is, in fact, associated with an interval of μ_D , rather than discrete values, D_k . Then, any discrete level of damage is intrinsically associated with a lower and an upper bound as well. Therefore, the approach proposed in this work is based on a range-based analysis where the accuracy of the results is given by the overlap of the ranges, not only by the proximity between the observed damage and the analytical values of the mean damage grade.

5.5 Results and discussion.

While carrying out the seismic assessment, it was noticed that the uncertainty was mainly concentrated in parameters BP6, BP9, BP11 and BP12. This was expected due to the poor information available for assessing the soil conditions (BP6), often limited to slope and the criterium of having a regional rock soil considered for the whole site. Parameter BP9 accumulated some uncertainties when assessing buildings that presented signs of modifications, namely with additions in the upper plans. Since references to diaphragms and roof systems are limited, BP11 and BP12 (floor slabs and roofs) are associated with a

certain generalised uncertainty when the existing images do not allow to have a clear perception of the structural system. As shown in Figure 5.4, there is a generalised low grading of the vulnerability class in the case of parameters BP2 and BP3, which can be partially explained by the poor masonry fabric of rubble stone and the conservative values adopted for assessing the loads and the characteristic compressive strength of masonry.

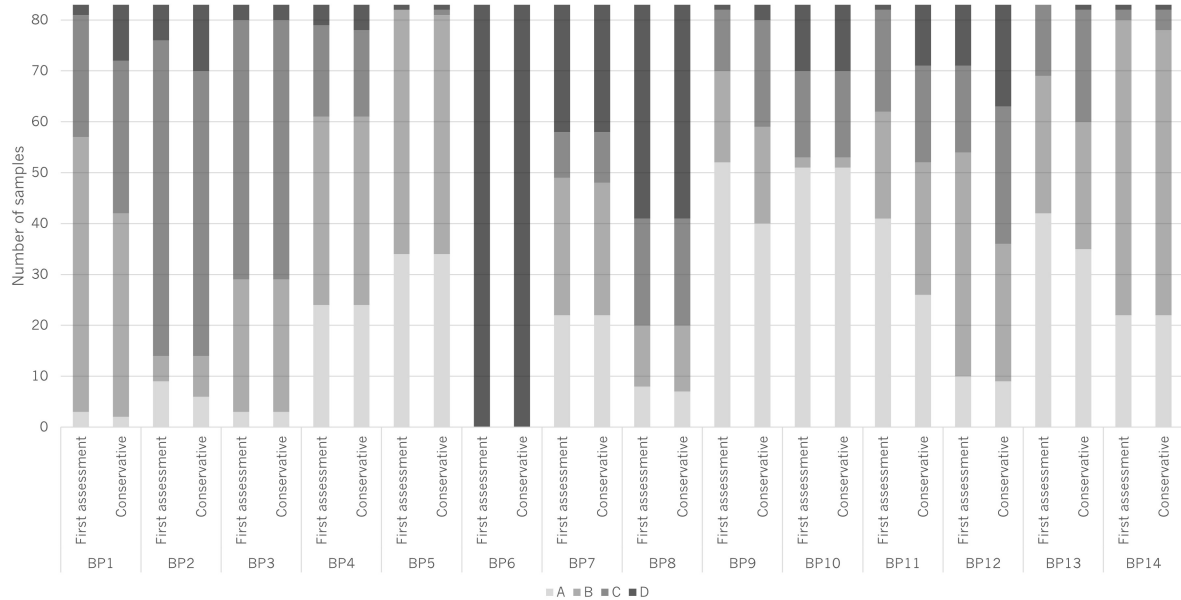
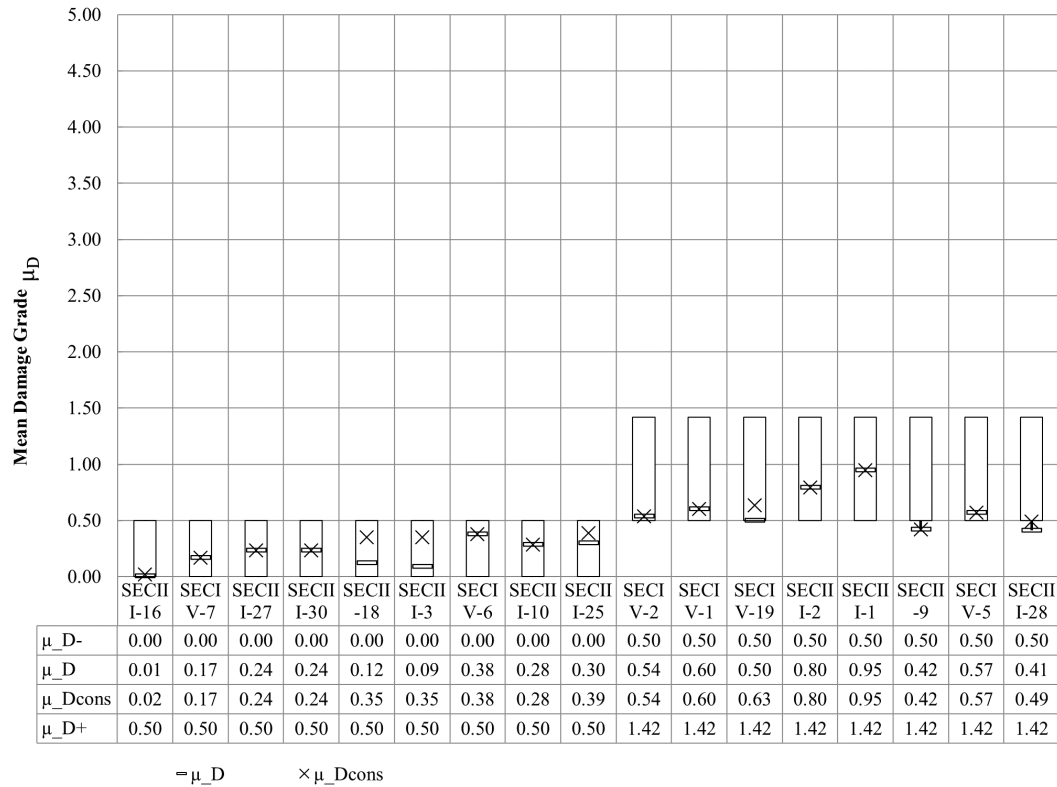
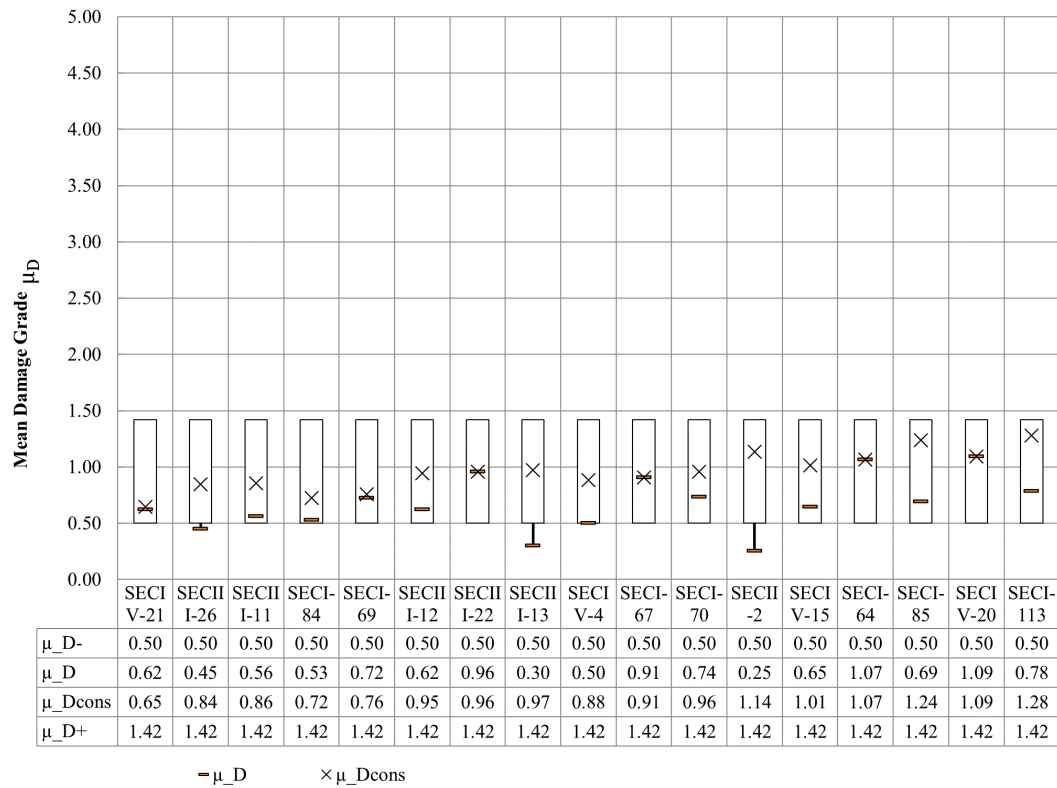
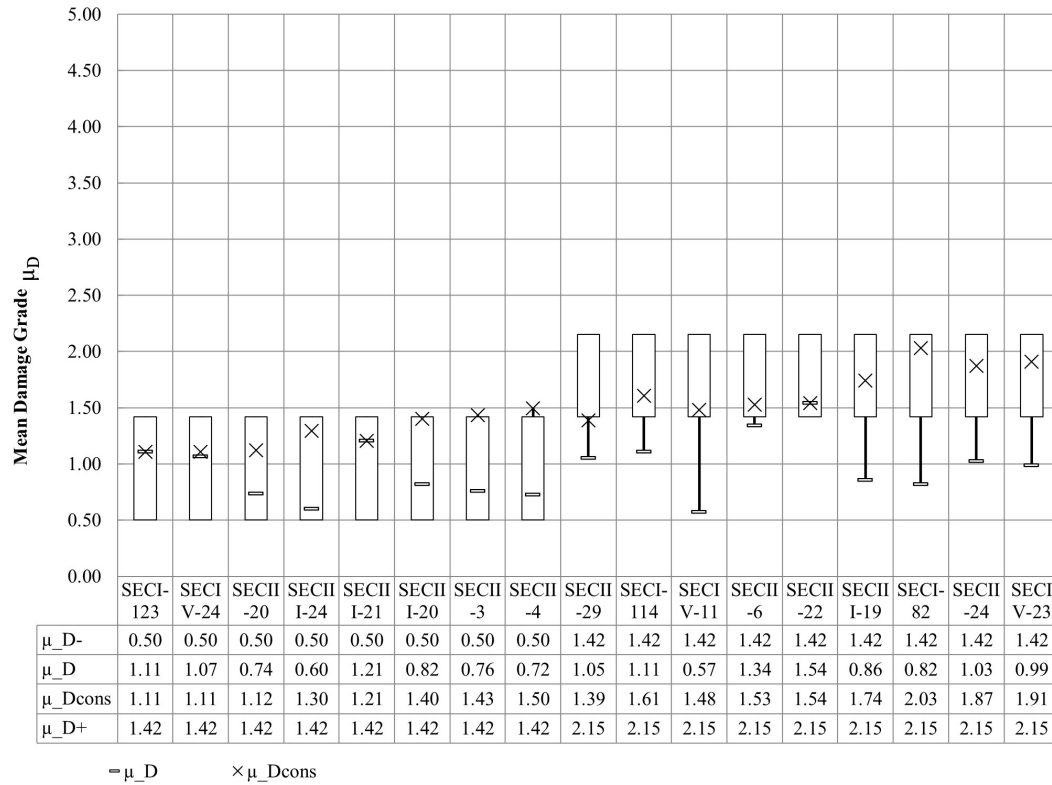
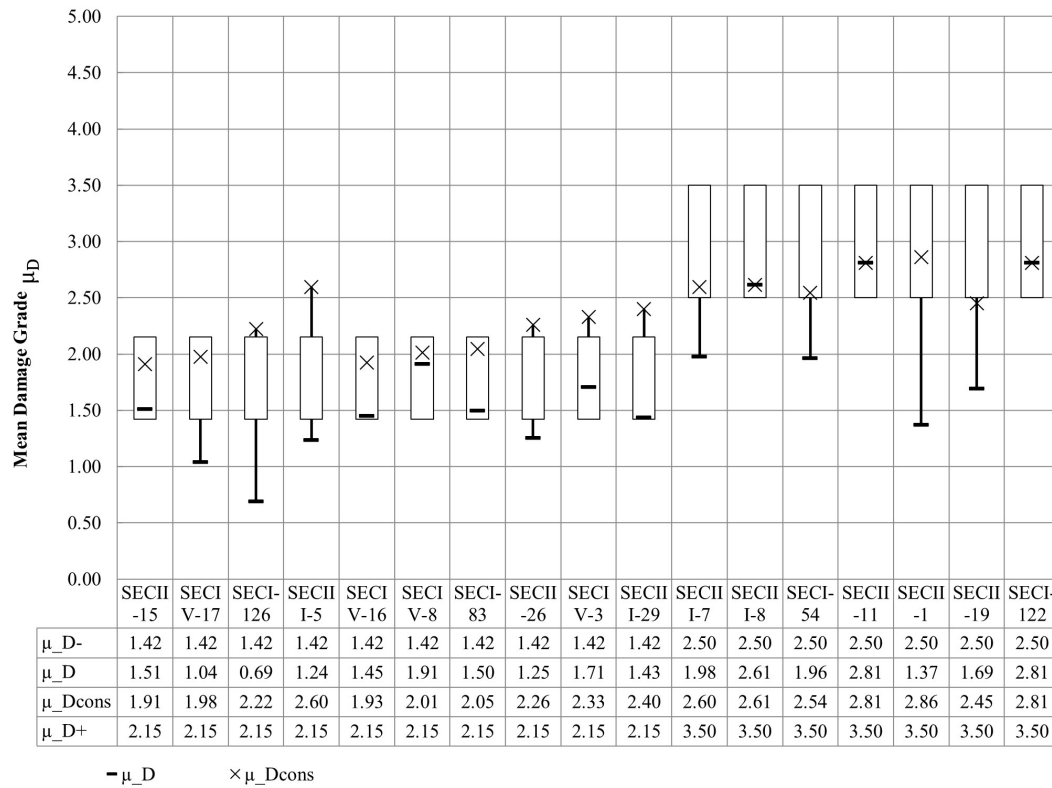


Figure 5.4: Vulnerability class distribution by parameter, considering the original and conservative approaches.

Some cases were especially difficult to assess since their typologies are not explicitly described within the method. Samples SECII-10, SECIII-1, SECIII-3, SECIV-1, and SECIV-2 are very illustrative examples, corresponding to buildings that are also galleries covering the pavements. The methodology led to conservative results, i.e., to analytical mean damage grades higher than the observed in the buildings. Figures 5.5, 5.6, 5.7, 5.8 and 5.9 contains a summary of the mean damage grade (μ_D) for each building according to the simple and conservative approaches in contrast to the lower and upper bounds that correspond to the observed discrete damage grade attributed after the seismic event.

The mean damage grade value among the sample was $\overline{\mu_D} = 1.28$ ($\sigma = 1.0$) with extreme values $\mu_{D,max} = 4.94$ and $\mu_{D,min} = 0.01$, while the conservative mean damage presented $\overline{\mu_{Dcons}} = 1.79$ ($\sigma = 1.25$) with extreme values $\mu_{Dcons,max} = 4.94$ and $\mu_{Dcons,min} = 0.02$. The Kolmogorov-Smirnov test was performed to assess the distributions' normality for both, μ_D and μ_{Dcons} values. For both series of results, the normality hypothesis H_0 is not supported at a significance level $\alpha = 0.05$, obtaining P-values of 3.59×10^{-6} for μ_D and 9.89×10^{-4} for μ_{Dcons} . The results, in fact, are significantly skewed to the left.

Figure 5.5: Summary of results (1/5). The interval between μ_D^- and μ_D^+ is represented as the white box.Figure 5.6: Summary of results (2/5). The interval between μ_D^- and μ_D^+ is represented as the white box.

Figure 5.7: Summary of results (3/5). The interval between μ_D^- and μ_D^+ is represented as the white box.Figure 5.8: Summary of results (4/5). The interval between μ_D^- and μ_D^+ is represented as the white box.

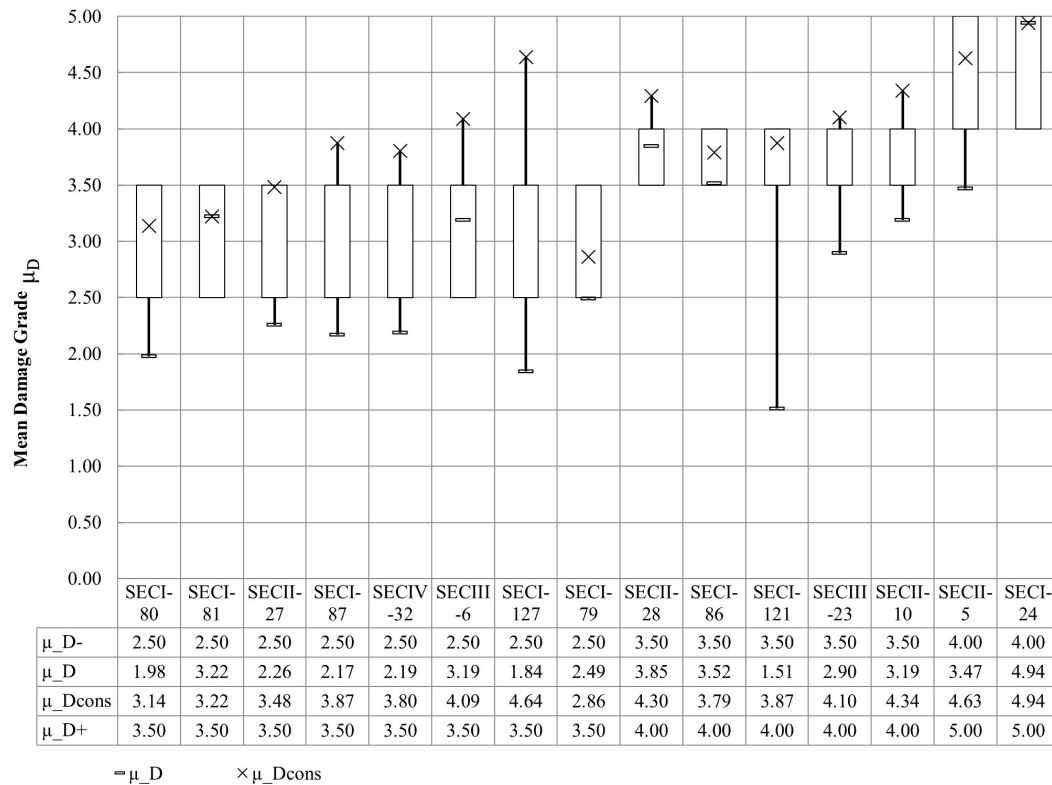


Figure 5.9: Summary of results (5/5). The interval between μ_D^- and μ_D^+ is represented as the white box.

For both assessments, samples SECI-24 and SECIII-16 presented the highest and lowest mean damage grade value, respectively. These figures also present the μ_D^- and μ_D^+ that respectively correspond to the level of damage observed in the building, according to the criterium explained in Table 8. This representation illustrates the overlap between the intervals of the mean damage grade obtained from the vulnerability index of the building and the actual level of damage suffered by the building.

When the ranges of the mean damage grades and the real discrete damages are plotted together, it is evident that a vast majority of values present an overlap. This is meaningful because it reveals a level of consistency towards the whole assessment. It is convenient to consider that the proportion of this overlap depends on numerous circumstances, such as the amplitude of the range for the discrete D_k values and the accumulation of uncertainties during the assessment process. Nevertheless, the tendencies exhibit a satisfactory pattern of proportionality and coherence.

It is worth noting that there can be a relevant distortion when dealing with the boundaries of the discrete damage values, given that the same semantical description may cover a wide variety of damages and patterns. This has been recognised as a potential limitation for using and calibrating this method, opening the possibility of developing more objective strategies for assessing damages in post-seismic scenarios.

Furthermore, it is important to mention that these results depend on the definition of the ductility factor, Q_1 , assumed equal to 1. Although this is the value suggested by the Mexican code for unreinforced masonry, the adoption of a ductility factor value based on experimental evidence is a most desirable improvement for any application of the method to any case.

As shown in Figure 5.10, there can be a relevant variation in the mean damage grades for some building cases, namely the ones with the lowest and highest mean damage grades. Adopting different values for the ductility factor, for example, a less conservative value, i.e., a value higher than the $Q=1.0$ considered here, will reduce the global dispersion of the mean damage grades of the set of buildings assessed.

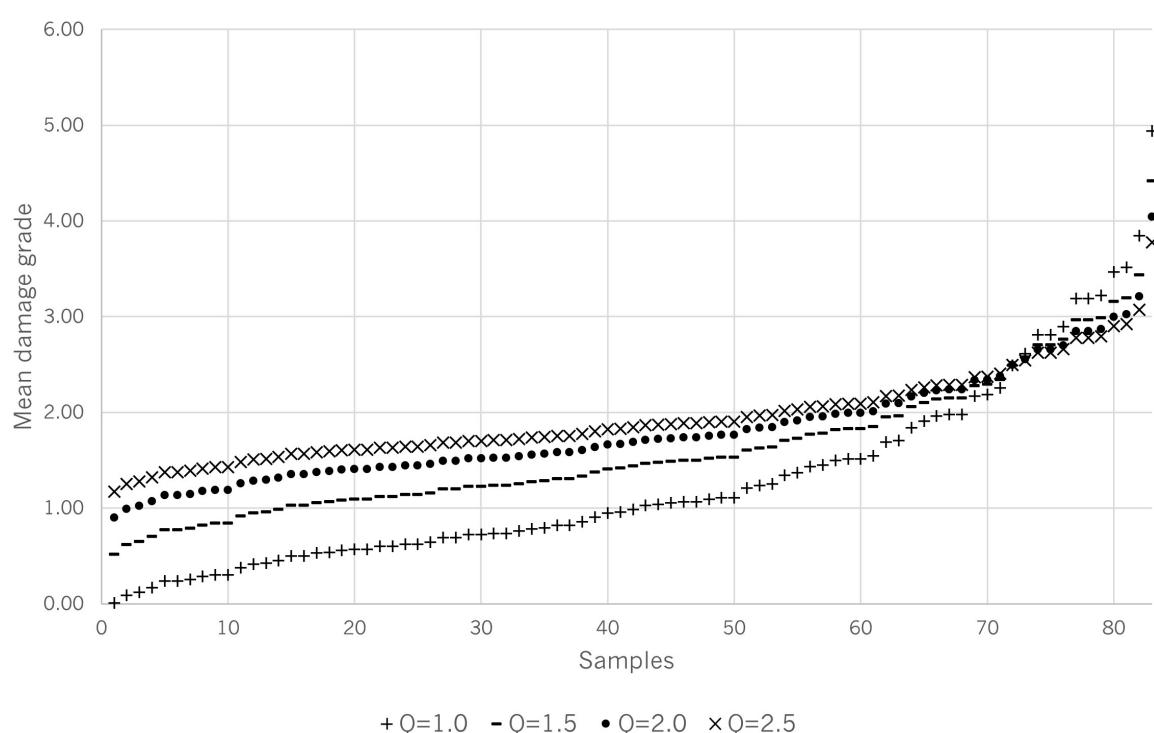


Figure 5.10: Variability of the Mean damage grades for the 83 constructions by using different values of ductility Q (The buildings were arranged from the lowest up to the highest mean damage grade value).

Although the mean damage grade values are important references for single-building qualitative assessment, it is possible to offer a contextualisation for an entire group of buildings, typologically similar in the same affected site, by means of a cartesian uncertainty/mean damage grade map. This representation facilitates the correlation between the distribution of the uncertainty level and the level of damage throughout a series of constructions, easily identifying how reliable the assessment of the vulnerability class is.

Since this map offers a contextualised comparative, it becomes possible to hierarchise further surveys (e.g., on those buildings that apparently present a high mean damage grade value combined with rela-

tively high uncertainty) and even immediate remedial actions (e.g., on those constructions that combine a relatively low uncertainty and a high mean damage grade.

In order to do so, the uncertainty has been graded by imposing numerical values associated with the levels: $QC0 = 0$; $QC1 = 0.33$; $QC2 = 0.67$; $QC3 = 1.00$. The uncertainty index UI is given by the sum of the value of the QC corresponding to each parameter multiplied by the weight that the parameter has in the seismic vulnerability method. Hence, uncertainty is proportional to the impact of the parameter. Finally, the result is divided by 15 (the sum of all (p_i) partial weights) to have a normalised value from 0 to 1, in which 1 represents an absolute uncertainty of all parameters, as per Eq. (5.7)

$$UI = \frac{\sum_{i=1}^{14} QC_i \times p_i}{15} \{0, 1\} \quad (5.7)$$

This phenomenon corresponds to a pattern in which the built environment is still rich in vernacular expressions and traditional construction techniques, especially in historical cities. It is relevant to point out that the investment for attending non-residential historical monuments (namely churches) would exceed 600 million USD [Lindero, 2017], concentrated in states with a high level of marginalisation. In fact, more than 50% of the historical buildings damaged by the 2017 Earthquakes are located in the states of Puebla and Oaxaca [García et al., 2018].

The upper and lower limit values for this index were a minimum $UI_{min} = 0.07$ for sample SECI-16, a maximum $UI_{max} = 0.54$ for sample SECII-29 respectively and a mean of $\overline{UI} = 0.37$ with a standard deviation $\sigma = 0.08$. This approach would facilitate the identification of the buildings assessed that combine a low quality of information but seem to have an elevated vulnerability index, becoming cases for further detailed appraisal and assessments.

On the other hand, a combination of a low uncertainty index and a low mean damage grade is desirable. The thresholds for this representation can be decided, for example, according to ranges of acceptability in terms of repair costs, establishing criteria for risk acceptability. Figure 5.11 presents an example based on the universe herein discussed.

The samples close to the bottom-left corner combine relatively low mean damage grades and low uncertainty, which is the safest condition in the context of the urban assessment. In contrast, samples in the dominion of the top-left corner combine relatively high mean damage grades with a relatively low degree of uncertainty. This means that these buildings are more likely to present a poor seismic performance – due to their high seismic vulnerability – and, consequently, deserve the most immediate attention. Samples in the top-right dominion present a high mean damage grade and relatively high uncertainty.

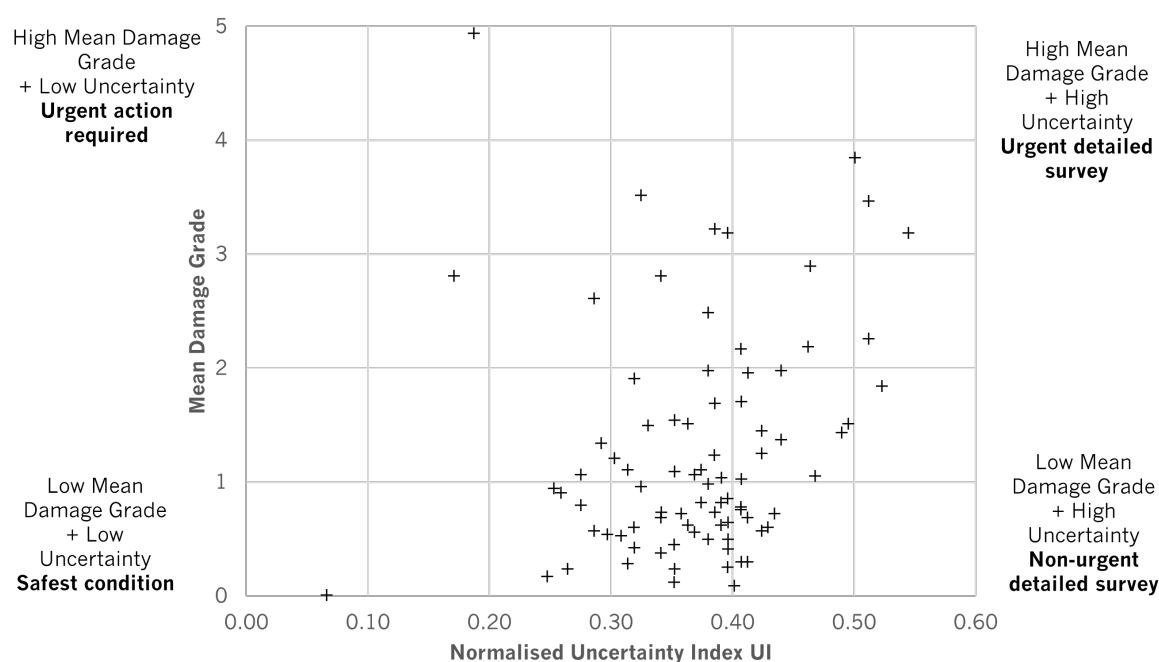


Figure 5.11: Distribution of the sample according to the calculated mean damage grade against the uncertainty index.

This may indicate that the damage grade is amplified by the lack of reliable information.

These buildings deserve particular attention as well, namely by carrying out urgent surveying actions devoted to double-checking their vulnerability, potentially resorting to more detailed assessment methodologies. Finally, the points closer to the bottom right corner of the graph refer to low vulnerable buildings. Although relatively high levels of uncertainty are associated with these buildings, their reassessment is not a priority, given that they are unlikely to suffer significant levels of damage. As is easy to understand for this analysis, this type of representation helps prioritise interventions, allowing for more efficient and rational use of the available resources. Table 5.10 summarises the distribution of damage grades throughout the studied universe.

The numerical values associated with the uncertainty are used for calculating mean values for the 83 constructions assessed. These mean values UI_p are then multiplied by the relative weight (p_i) of each parameter for assessing the relative impact that the uncertainty had on the vulnerability assessments carried out in this work. This exercise points out that the most significant distortions due to epistemic uncertainties are on parameters BP1, BP12 and BP2. A detailed survey campaign specifically devoted to minimising the uncertainty on these parameters would be reflected in a substantial reduction of the overall uncertainty throughout the universe of study.

Both, the Uncertainty Index and the Conservative Mean Damage Grade, constitutes feasible strategy to deal with uncertainty when having a partial availability or lack of data. The example of the National

Parameters (BP)	Class C_{vi}				p_i	UI_p	UI^*p_i
	A	B	C	D			
Group 1. Structural building system							
1. Type of resisting system	3.61%	65.06%	28.92%	2.41%	2.50	0.43	1.07
2. Quality of the resisting system	10.84%	6.02%	74.70%	8.43%	2.50	0.36	0.90
3. Conventional strength	3.61%	31.33%	61.45%	3.61%	1.00	0.32	0.32
4. Maximum distance between walls	28.92%	44.58%	21.69%	4.82%	0.50	0.30	0.15
5. Number of floors	40.96%	57.83%	0.00%	1.20%	0.50	0.30	0.15
6. Location and soil conditions	0.00%	100.00%	0.00%	0.00%	0.50	0.87	0.44
Group 2. Irregularities and interaction							
7. Aggregate position and interaction	26.51%	32.53%	10.84%	30.12%	1.50	0.22	0.33
8. Plan configuration	9.64%	14.46%	25.30%	50.60%	0.50	0.32	0.16
9. Height regularity	62.65%	22.89%	13.25%	1.20%	0.50	0.38	0.19
10. Wall façade openings and alignment	61.45%	2.41%	20.48%	15.66%	0.50	0.12	0.06
Group 3. Floor slabs and roofs							
11. Horizontal diaphragms	49.40%	25.30%	24.10%	1.20%	0.75	0.47	0.35
12. Roofing system	12.05%	53.01%	20.48%	14.46%	2.00	0.47	0.93
Group 4. Conservation status and other elements							
13. Fragilities and conservation status	50.60%	32.53%	16.87%	0.00%	1.00	0.38	0.38
14. Non-structural elements	26.51%	69.88%	2.41%	1.20%	0.75	0.22	0.17

Table 5.10: Example of conservative grades obtained after combining different grades and QC levels.

Catalogue for Historical Monuments is an example of this, given that there is a vast universe of buildings that have been documented with variable levels of accuracy. Even if, in many cases, the information is not considered enough for performing detailed seismic vulnerability assessment, the information they provide is relevant and represent a valuable opportunity to complement with aspects to be enhanced.

Such vulnerability assessment involving the evaluation of a large number of parameters and enclosing information related to historical monuments in individual datasheets, clearly benefits from a graphical representation in a simplified and easy-to-use scheme that is helpful for easily communicating the vulnerability of a construction together with the level of uncertainty that its survey has at a determined moment in order to provide a more accurate description during field campaigns. Figure 5.2 shown in Section 3.2 is herein revisited to exemplify the assessment for the building SECII-27 (Figure 5.12).

In this visual example, parameters such as BP2 obtained a grade A. Thus, since grade A has a numerical value of zero, no section is shadowed in the corresponding sector. Parameter BP6 was evaluated initially with grade B, which is associated with a numerical value and consequently, the most inner circle sector or slice is colour filled (dark gray). Nevertheless, as referred previously, uncertainty regarding this grading is to be considered and the light-shadowed sectors or slices (in light gray) imply that the parameter can potentially be graded as C or D.

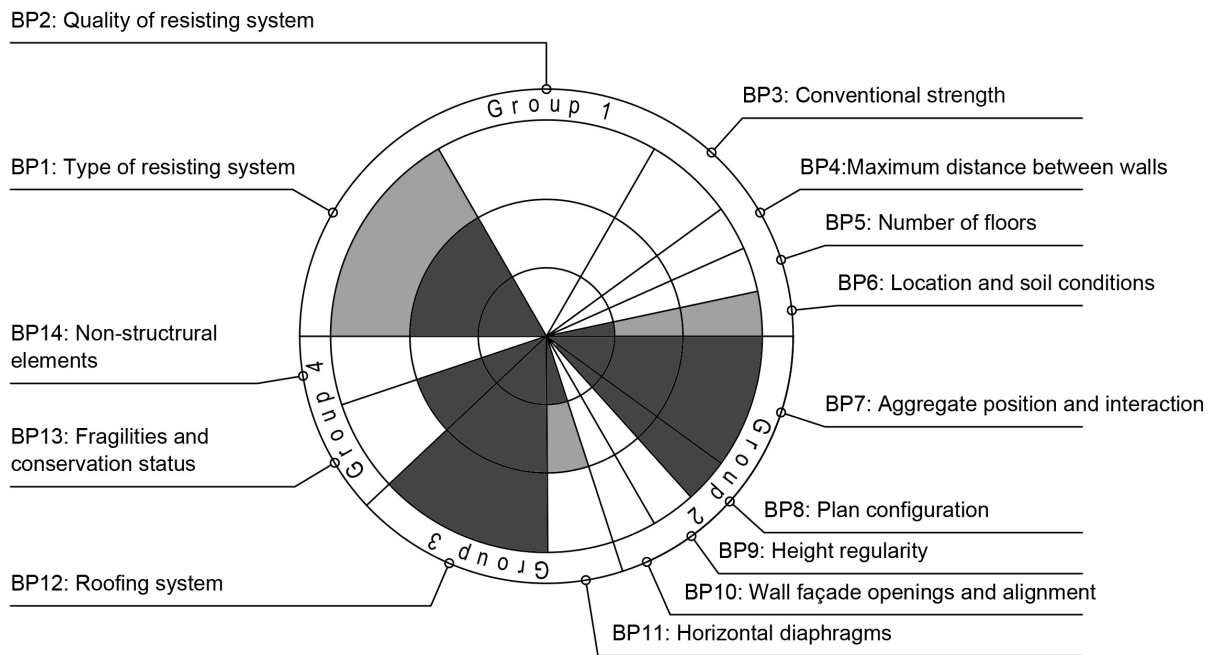


Figure 5.12: Example of a graphical representation for the building SECII-27.

This implies a Quality Check assessment $QC = 2$ or $QC = 3$. Furthermore, the presence of the light-shadowed sectors indicates the need for further surveying of this parameter, BP6. Given that the sizes of the sectors or slices are geometrically proportional to the grade values and relative weights, the observation of such a graphical output allows correlating that a more colour-filled figure implies a higher vulnerability index. Additionally, another useful interpretation of this graphical output is uncertainty on the assessment of some parameters, indicated by the presence of lighter coloured sectors.

5.6 Final remarks.

Seismic risk represents a relevant agent for human settlements, given the grade of destructiveness that a single event can impose. Furthermore, experiences such as the 2017 Earthquakes in Mexico demonstrate the relevance of promoting awareness through simple to more complex approaches to assess the structural and seismic vulnerability of traditional constructions to cultural assets. It is acknowledged that

previous works devoted to risk prevention and assessment in the Mexican context are noteworthy; however, the large-scale assessment of historical constructions is still a gap. Nevertheless, the existence of a National Catalogue of Historical Monuments presents an interesting opportunity for performing simplified approaches, resorting to the Vulnerability Index Method, herein presented, adapted and exposed.

The present document implemented the Vulnerability Index Method approach for assessing a total of 83 buildings/constructions in the historic city of Atlixco, Puebla. Adopting this method demanded performing a detailed analysis of all parameters for the building and façade approach to assess the necessary slight redefinition and adapting criteria. A nuclear part of this exercise has been the adjustment of the parameters in order to fit the criteria to the Mexican built environment. This process demanded more than a translation but decoding the rationale and the justification behind the criteria. Despite the great value of the available information, the sources of data presented several gaps during the data-acquisition process. Given the difficulties for addressing them by performing on-site visits, a framework for contextualising and documenting the uncertainty was developed. This strategy is aimed to be adopted as a response to the lack of information, a common issue when reviewing existing databases. The implementation of a strategy based on assuming the uncertainty for defining plausible ranges for the vulnerability index and consequently the mean damage grades, instead of closed values resulted coherent and suitable for testing the methodology against the observed damages after the 19th of September 2017 event.

The results of the assessment exhibit a good correspondence between the forecasted mean damage grades with the real and observed damage in buildings. This qualitative correspondence suggests the suitability of using this approach for assessing masonry structures in Mexico, accepting the eventual need of adapting the criteria for vulnerability class grading (such as herein presented). The strategies herein presented for contextualising and documenting the uncertainty during data acquisition are more than an instrumental assumption. Those strategies are meant for using existing information as a starting point regardless of its accuracy or quality, not overlooking the issue and taking it into account for a more robust analysis. Even if the present state of information is considered insufficient for performing large-scale seismic vulnerability assessments, the information contained can be complemented with additional information that could be seen as to be included into the current updates of the datasheets of the National Catalogue. If information is scarce and potentially leading to a range of values for the seismic vulnerability indices and mean damage grade values, the definition of a qualitative comparison and other graphical analysis would facilitate the use of that information for decision-making.

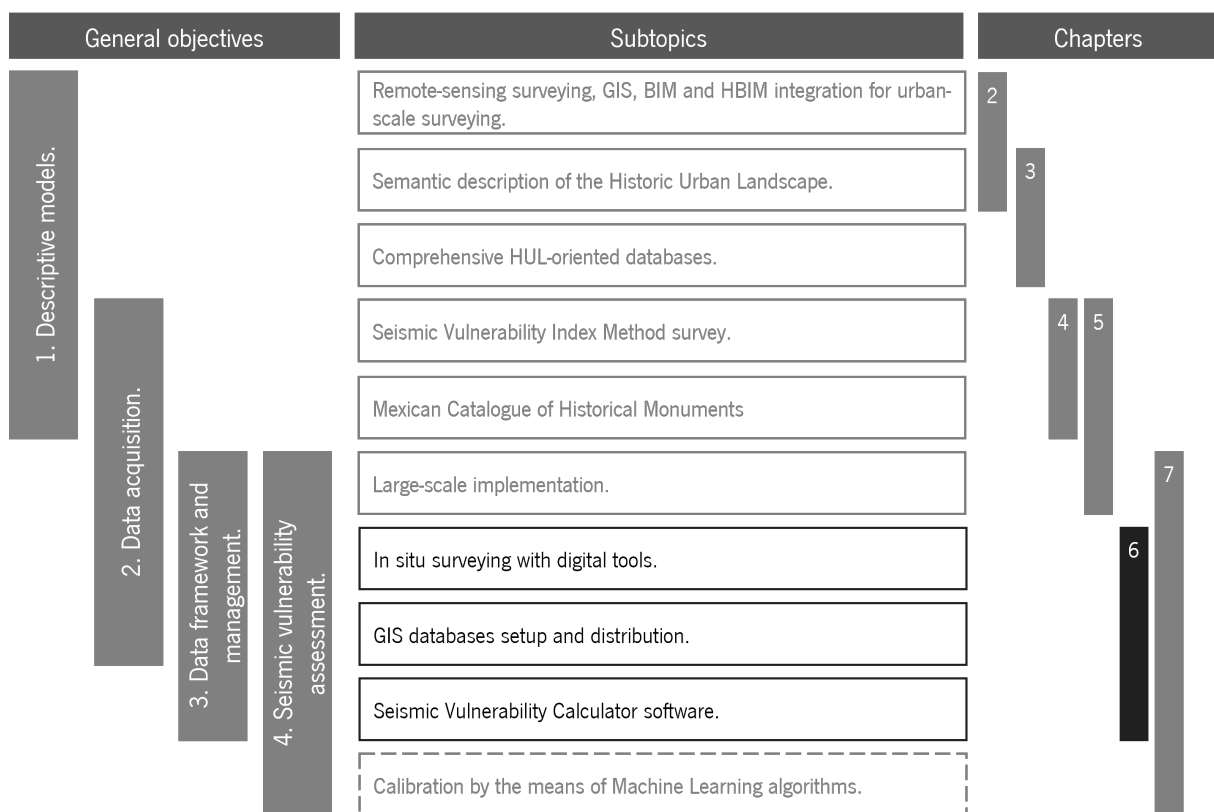
The results and the ability to use this method for assessing the seismic vulnerability of masonry constructions in Mexico may be limited because of the representativeness of the buildings of Atlixco when

compared to different built environments in the country. However, it is important to note that no relevant typological divergences from the typical constructions of the central region of the country were found. All the parameters of the method were suitable for assessing the constructions, supporting the adoption of this method for other environments in which the parameters (and their grading conditions) are reasonably applicable. The hypothesis of extrapolating the method to another construction environment that fits the conditions considered in Appendix B is then sustained. Nevertheless, it is convenient to consider the relevance of testing the approach in the context of experimental data for more accurate grading and selection of ductility values. Another opportunity for enhancement lies in defining a more-suitable scale for damages, consistent with the common failures and mechanisms found in the Mexican built environment, including the adoption of continuous grade scales instead of closed discrete grades for assessing some quantitative parameters.

The ranges for real/observed damage and the forecasted/calculated mean damage grade are often overlapped, representing a good precedent for performing a series of potential future works that would improve the application of this approach. An experience with more accurate data (i.e., with a better resolution) would facilitate performing sensibility analysis for testing numerous possibilities under the basis of the results herein presented. For example, adjustments on the parameter's weights, the impact of the suppression of some parameters that present no variability among the samples or even the inclusion of new parameters, using data from the Mexican National Atlas of Risk or social vulnerability indicators for involving more stakeholders interested in the impact of seismic risk in human settlements are foreseen.

Chapter 6

Implementation of Open-Source GIS databases for vulnerability assessment.



Rafael Ramírez Eudave, Daniel Rodrigues, Tiago M. Ferreira and Romeu Vicente (2023) *Implementing Open-Source Information Systems for Assessing and Managing the Seismic Vulnerability of Historical Constructions*, Buildings 12 (2), 540. DOI: 10.3390/buildings13020540

Abstract

The characterisation of the seismic vulnerability of historical constructions represents a complex problem in which the typological variability, the difficulty of performing reliable large-scale assessments and dealing with a large database all play a role. Nevertheless, reducing the uncertainty regarding the structural vulnerability of the existing building stock (mostly for small and/or isolated human settlements) is key for risk assessment and management. The present work proposes a novel approach based on the integration of a series of open-source tools for assembling a vulnerability-oriented database that is linked to a series of external services for increasing its capabilities. The database was implemented in a Geographical Information System (GIS) environment and contains the survey of a seismic vulnerability index for masonry constructions based on an adapted version of the GNDT-II approach. A customised Python-based software for reading, managing and editing the database is herein presented. This program allows the execution of the most typical operations with no assistance from the GIS environment, facilitating user interaction. Furthermore, the calculations regarding the vulnerability index and levels of damage have been implemented in this program. Alternatives for distributing the database are implemented and discussed, such as cloud-based distribution and the use of the Transactional Web Feature Service (WFS-T) protocol for its virtual publishing. The entire framework herein presented is a replicable and feasible workflow that can be set even with reduced infrastructure, allowing a progressive enlargement.

6.1 Introduction.

This work contains and expands the findings presented at the 10th ReUSO Documentation, Restoration and Reuse of Heritage Congress (Porto, Portugal, 2022) [Ramirez Eudave et al., 2022b].

The characterisation of the seismic vulnerability of large groups of buildings is a challenging task in which material and human resources must be optimised to obtain reliable information in a reasonable amount of time. Despite several simplified approaches that have been found suitable for assessing the seismic vulnerability of historical constructions, many of them require a customised approach regarding structural surveying instead of applying more generalised characterisations. For example, the analysis of mechanisms of collapse [D'Ayala et al., 1997] requires detailed knowledge of the structure, the retrofitting and strengthening actions. This approach may not be suitable for obtaining information from large sets of constructions in which access is not always granted. The use of numerical models (e.g., BIM, HBIM and FMA models) is suitable when the mechanical characterisation of the components and materials is reasonably well defined [Lo Turco et al., 2016, Brumana et al., 2019]. Nevertheless, these approaches can be found limited when such characterisation is not reliable or available. Some other simplified approaches are centred on offering a partial assessment of the buildings, such as the mechanical characterisation of the structural elements. A relevant method in this context is that of the Masonry Quality Index (MQI), which allows a fairly good estimation of the mechanical properties of masonry walls based on a series of features related to the constitution, arrangement and quality of the masonry fabrics well as the components of the system [Borri et al., 2015]. Despite their utility, these strategies may not represent the overall behaviour or vulnerability of the structure. Therefore, for achieving a more representative assessment it becomes necessary to perform both comprehensive and straightforward survey strategies that can allow recognising a structure based on a limited (and desirable standardised) set of paramount building features.

This condition is compatible with the implementation of simplified and often parametric approaches, namely based on the material and geometrical properties of structures. These strategies, widely discussed by Bektaş and Kegyes-Brassai [2022], are relatively easy to implement if such characterisation is based on classifying features (i.e., categorising features within a limited range or a discrete number of classes) instead of performing customised surveys. However, it is still common to perform data-acquisition campaigns based on paper datasheets that are later transferred and managed on informatics platforms. Some examples of this approach are given in the Rapid Seismic Vulnerability Assessment developed by Nanda and Majhi [2014], the survey form for masonry buildings of Giuliani [2020], the model of the Bihar State Disaster Management Authority (India) [Sinha and Kumar, 2022] or the CARTIS datasheet for the typology

logical characterisation towards seismic risk [Zuccaro et al., 2016]. There are territorial-scale applications that have used similar approaches for assessing other types of vulnerabilities, such as the implementation performed by Salvati et al. [2021] for assessing geohydrological hazards.

This approach has several advantages because of the relatively small amount of resources that are needed but can become problematic when applied to large-scale samples, such as urban-scale sets of constructions. Furthermore, these problems can be increased when dealing with emergencies, such as post-seismic data acquisition. In this context, the optimisation of these campaigns by using computational resources is a promising alternative. Some relevant examples in this sense are devoted to the automatic characterisation of external features by using machine-learning methods (such as the Vulnerability Analysis and Machine Learning—VULMA—developed by Ruggieri et al. [2021], or the design of damage functions based on typological categorisations, such as the one designed by Rosti et al. [2021]).

The use of digital tools for minimising the bridge between the on-field campaigns and outcomes obtention is still an open field in which a feasible and straightforward workflow could become a valuable resource for implementing large-scale seismic vulnerability assessments even for settlements in which human, computational and material resources are limited. This situation is common in many countries in which masonry buildings are still predominant for satisfying housing needs (e.g., in the Mediterranean region, the Middle East and Latin America) [United Nations Office for Disaster Risk Reduction, 2017].

Even within the same country, the capacity for assessing building stock after strong seismic events can be very asymmetrical, with notorious differences between big and relatively small human settlements. The 2017 Earthquakes in Mexico are particular examples of how the structural reconnaissance and needed survey almost immediately reached the capital and the surrounding areas Galvis et al. [2017] Ramírez Eudave and Ferreira [2021d], while the information regarding the survey and number of damaged structures was much slower in smaller (often isolated) regions [Alberto et al., 2018]. This fact invites us to consider how these large-scale assessment approaches can become standardised civil protection procedures for enhancing emergency response and resource management. Despite this work presenting an implementation based on a proactive survey (i.e., for assessing the seismic vulnerability of historical constructions), it becomes important to consider that it can be implemented for performing reactive post-event data acquisition surveys. An easy-to-apply workflow is herein presented, emphasising the suitability and convenience of being implemented with open-source and free tools, facilitating its adoption and replication.

6.2 The VIM methodology for assessing the seismic vulnerability of masonry buildings.

Gavarini [2001] states that «...the seismic vulnerability of a building is a quantity associated with its ‘weakness’ in front of earthquakes of a given intensity so that the value of this quantity and the knowledge of seismic hazard allow to evaluate the expected damages from future earthquakes». Determining how to measure this “weakness”, however, is the object of numerous approaches with different levels of complexity and accuracy [Maio et al., 2018].

This problem becomes even more complex when dealing with masonry structures, in which the vast variety of materials, typologies and heterogeneity of solutions create difficulty in the adoption of generalised assumptions [Roca et al., 2010]. Furthermore, the study of ancient structures adds a significantly large number of uncertainty sources, mostly related to the state of conservation, the presence of different construction stages and long-term soil-structure interactions.

When dealing with large samples of constructions (e.g., in the context of a Historic Urban Landscape [Ramírez Eudave and Ferreira, 2021c], it is convenient to use simplified standardised approaches for certain typologies. In the case of masonry constructions, the GNDT-II method has been widely used, calibrated and adapted. The original proposal [Gruppo Nazionale per la Difesa dai Terremoti—GNDT, 1994] considered ten parameters that rule the seismic behaviour of unreinforced masonry buildings.

Subsequent calibrations led to the inclusion of additional evaluation parameters keeping, however, the original rationale—each parameter is evaluated through four vulnerability classes corresponding to increasing levels of vulnerability, which are then associated with weights whose value represents the relative significance of that parameter for the global seismic vulnerability of the building [Ferreira et al., 2017a]. These parameters comprise a series of qualitative and quantitative descriptors, such as geometrical and material features of the constructions. It is convenient to recall, however, that some of these parameters are meant to be categorised according to expert decisions and may be subjected to some subjective judgements.

The descriptive model used for this workflow (from here named Vulnerability Index-based Methodology or “VIM”) is the calibration used for the city of Atlixco (Puebla, México) of Ramírez Eudave and Ferreira [2021d], with a total of 14 parameters (Table 6.1).

This methodology allows calculating a vulnerability index (Eq. (6.1)), which, for ease of use, is usually normalised to range from 0 to 100 (Eq. (6.2)). This normalised value can be subsequently used to calculate the vulnerability value V (Eq. (6.3)), which, in turn, together with the ductility of the structure (Q)

and the macroseismic intensity I_{EMS-98} allows for the estimation of a mean damage grade, μ_D , as per Eq. (6.4), considering an adjustment for seismic intensities lower than 7 (Eq. (6.5)). Equations (6.1) to (6.5) have been adopted from the experience reported by Ramírez Eudave and Ferreira [2021d].

Parameters	Class C_{vi}				Weight p_i	Relative weight
	A	B	C	D		
Group 1 Structural building system						50/100
BP1. Type of the resisting system	0	5	20	50	2.50	
BP2. Quality of the resisting system	0	5	20	50	2.50	
BP3. Conventional strength	0	5	20	50	1.00	
BP4. Maximum distance between the walls	0	5	20	50	0.50	
BP5. Number of floors	0	5	20	50	0.50	
BP6. Location and soil condition	0	5	20	50	0.50	
Group 2 Irregularities and interaction						20/100
BP7. Aggregate position and interaction	0	5	20	50	1.50	
BP8. Plan configuration	0	5	20	50	0.50	
BP9. Height regularity	0	5	20	50	0.50	
BP10. Wall façade openings and alignment	0	5	20	50	0.50	
Group 3 Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	
BP12. Roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						12/100
BP13. Fragilities and conservation status	0	5	20	50	1.00	
BP14. Non-structural elements	0	5	20	50	0.75	

Table 6.1: Parameters for the VIM approach based on Ramírez Eudave and Ferreira [2021d].

$$I_{vf}^* = \sum_{i=1}^{14} c_{vi} p_i \quad (6.1)$$

$$I_v = \frac{I_{vf}^* \times 100}{750} \quad (6.2)$$

$$V = 0.592 + 0.0057 \times I_{vf} \quad (6.3)$$

$$\mu_D = \left[2.5 + 3 \times \tanh \left(\frac{I_{EMS-98} + 6.25 \times V - 12.7}{Q} \right) \right] \times f(V, I); 0 \leq \mu_D \leq 5 \quad (6.4)$$

$$f(V, I) = \begin{cases} e^{\frac{V}{2 \times I - 7}} & I \leq 7 \\ 1 & I \geq 7 \end{cases} \quad (6.5)$$

The mean damage grade μ_D is especially significative for establishing a correlation between the macroscopic evidence of damage (based on the presence of cracks, deformations, detachments, etc) and the numeric levels of damage, having comparative (yet relatively subjective) thresholds. A practical systematisation of this methodology is relevant for performing urban-scale assessments and would desirably include the parameters' acquisition, the data treatment for calculating the vulnerability index and damage grades in the context of a certain seismic event.

6.3 Geodatabases for managing the GNDT-II survey.

Using geodatabases is an efficient way of systematising the information related to vulnerability index-based approaches [Ramírez Eudave and Ferreira, 2021b]. These environments facilitate the association of multiple types of data on georeferenced entities (points, lines, polygons, etc.). Hence, these environments are very suitable for capturing, managing and displaying vulnerability-related surveys and outputs. The use of GIS is also very compatible with some other risk-related applications, such as seismic intensity maps and social vulnerability layers of information, becoming an enlargeable and robust base for developments.

A very common free and open-source software for this purpose is QGIS [QGIS Development Team, 2021]. This project of the OSGeo Foundation is widely known and used for different purposes, including research. Given its popularity, there is a continuous development of plug-ins and enhancements from independent actors, facilitating a flexible and customisable use of this tool. The high interoperability between QGIS and some commercial software is favoured by the use of open (non-proprietary) standards for data format, such as the GeoPackage format (developed by the Open Geospatial Consortium—OGC).

QGIS data organisation depends on managing several layers with geographical and geometrical entities in which every instance is related to several attributes with numeric, alphanumerical, Boolean or other types of data (Figure ??). This attribute table can contain all the fields needed for performing the VIM approach in direct association with the spatial location of the construction. The setup and replicability of these (and other) customised attribute tables can be guaranteed by developing them by the means of Python-based scripts, that are easily run on a devoted console. These scripts facilitate setting the name of the variable, the type of data and the characteristics that the field can register (length, close lists of options, range of values, etc.).

Since layers can be stored (and managed) as independent GeoPackage files, it is possible to perform both read and write operations externally to the GIS software. It is also possible to publish and consult the layers from remote services, such as online sources. These actions can become very significant

when sharing information among numerous stakeholders and professionals that are not familiar with GIS platforms and standards. This is a typical situation when performing risk assessments.

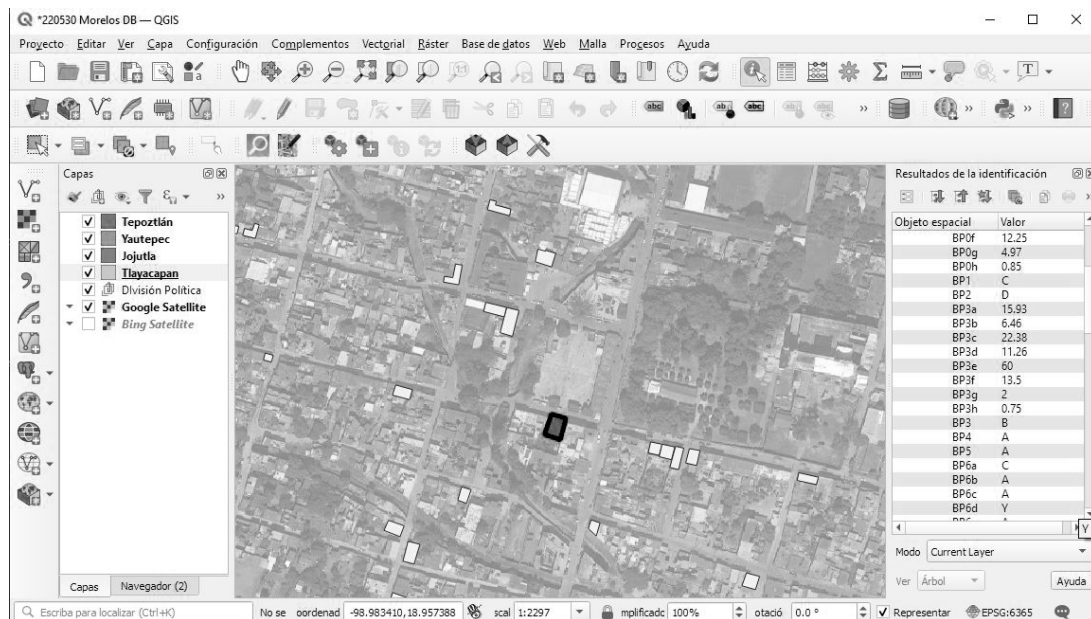


Figure 6.1: Screenshot of QGIS interface. The active layer includes a series of features associated to the Parametric Seismic Vulnerability Index for a specific set of constructions.

Some of the most relevant capabilities for a VIM-oriented geodatabase are summarised in Figure 6.2 and will be discussed in the subsequent sections. The general components of this dataflow are the input data block (the sources from which it is possible to obtain the description of the physical reality), a local PC system in which the GIS environment and the Python language-based front end are executed, a remote server in which the GIS layers can be published and updated from the locally-stored database and, finally, a cloud-based online distribution that allows accessing the database from mobile devices.

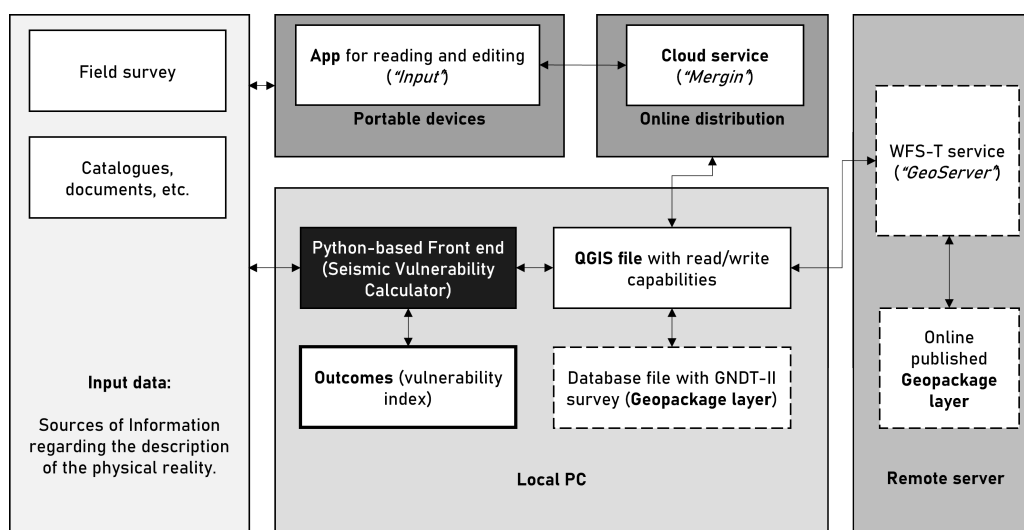


Figure 6.2: Integrated data flow on GIS databases for VIM surveys.

It is worth noticing that the core of the dataflow is the Python-based front end since it is an interface for adding and reading data, interacting with the database and calculating the outcomes (vulnerability index, levels of damage, etc.). As explained in the following sections, the GIS environment is mostly used for extending the capabilities of the database by interacting with cloud-based storage (for complying with the survey in situ) and the remote server.

6.4 Complementary resources for GIS data acquisition and management.

The presented workflow (Figure 6.2) schematises the role that some complementary tools can have for complementing the QGIS capabilities as a VIM database, namely for performing read/write operations outside of QGIS software through a front-end software and remote services for hosting GIS layers or QGIS files (WFS-T protocol and MerginMaps services). In the context of the seismic assessment of historical constructions, this workflow is specifically significant for performing large-scale diagnosis by the means of remote access and real-time synchronisation.

6.4.1 Front-End (Seismic Vulnerability Calculator) software.

It is always important to consider that many potential actors involved in the field data-acquisition stages could not be familiar with GIS environments and data structures. Therefore, providing a limited but straightforward environment for adding and reading data can represent a valuable strategy for minimising the risk of negatively affecting the subjacent GIS database while providing a robust and safe environment for data reading and writing. In this context, a graphic interface based on Python language can be an appropriate step for easing the interpretation, management, edition, and calculations related to data stored in GIS layers by using a dedicated user interface (Fig. 6.3).

This program (Seismic Vulnerability Calculator) [Ramirez Eudave, 2022] permits reading different formats of GIS layers (such as GeoPackage and Shapefile standards) thanks to the use of the Geopandas [Jordahl et al., 2020] library. This library is an adaptation of the Pandas data framework that includes compatibility with geographical features and keeping the integrity of geographical data while working on the attribute table of the layer.

The capabilities of the Geopandas library, together with the Graphical User Interface (GUI) package Tkinter [Lundh, 1999], permitted the development of an easy-to-use interface in which all the parameters (and sub-parameters) are displayed for their read, capture and edition.

Seismic Vulnerability Calculator v. 1.4 (January 2023)

(A) Main Input Module:

Parameter	Value	Info
Conservation	Reguli	
0a. Height	5.0	
0e. Storeys	1.0	
0f. Facade_a	20.45	
0g. Facade_b	14.54	
0h. Facade_s	0.5	
3a. W_Area_x	30.68	
3b. W_Area_y	44.99	
3c. W_Area_t	75.67	
3d. L_Span_P	11.82	
3e. tau_k *	60.0	
3f. p_m *	13.5	
3g. l_w	2.0	
3h. p_s *	2.5	
6a. Soil	D	
6b. Slope	A	
6c. Delta_h	A	
6d. Foundation	Y	
8a. Plan (a)	14.54	
8b. Plan (b)	0.0	
12a. Roof thrust	A	
12b. Perim. reinf.	N	

(B) Geopackage file module:

Geopackage file: Atlixco | Load data | About | Exit

Parameters in RED can be automatically obtained having all those in BLACK fulfilled

The vulnerability index can be automatically calculated having all BLACK and RED parameters

Update | Reset | Auto+Upd | MQI CALC

Key	Address	MQI_Sv	MQI_SD	MQI_SS	MQI_Wv	MQI_HJ	MQI
2.0	015 Pedro Baranda 207	F	NF	NF	PF	F	NF
3.0	025 Sor Juana Ines de la Cruz	PF	PF	F	NF	F	PF
4.0	026 Covarrubias 101	F	PF	NF	F	F	F
5.0	028 Zayas Enriquez 123	F	PF	F	F	PF	PF
7.0	034 Jesús H. Preciado 102	F	F	PF	F	PF	PF
9.0	038 Francisco Javier Mina no.	F	PF	PF	F	PF	F

(C) Suggested grades according to the given data:

BP2: D BP3: A BP4: D BP6: C BP8: D BP12: D

Regular Expected damage D5: Failure. Total in-plane or out-of-plane failure

Conservative Expected damage D5: Failure. Total in-plane or out-of-plane failure

Intervals of damage 0:[0-0.50], 1:[0.50-1.42], 2:[1.42-2.50], 3:[2.50-3.50], 4:[3.50-4.00], 5:[4.00-5.00]

(D) Material properties module:

Material	MQI_V	MQI_I	MQI_O
SM Mech. prop. & cons.	3.92	3.18	2.94
SD Stone/brick dim. prop.	Min	Mean	Max
SS Stone/brick shape	0	0	0
WC Wall leaf connections	0	0	0
HJ Horizontal bed joints	0	0	0
VJ Vertical bed joints	0	0	0
MM Mortar properties	0	0	0
Thick bed joints	0	0	0

Figure 6.3: The main window of the seismic vulnerability calculator and the display modules (A–D).

This interface offers four display modules. The main module (A) includes a box for searching any given entry from the building key and all the parameters and sub-parameters that conform to the vulnerability index method. These sub-parameters comprise the information needed for automatically obtaining the quantitative parameters. All the parameters that are calculated this way are shown in red colour, advising the user. For example, the selection of a type of masonry (“0a. Type of Masonry”) is automatically associated with the “ τ_{u_k} ” characteristic shear strength preloaded in the script.

Each parameter is also associated with a series of “Quality Check” (QC) indicators, meant to indicate how certain the surveyor is about the grading process [Ramírez Eudave et al., 2022]. This module also offers the vulnerability index and mean damage grades that are obtained given the macro-seismic intensity MMI and the ductility factor Q . Furthermore, every parameter is associated with a “More” button that displays an explanatory dialogue for the user to contextualise the magnitudes and characteristics to be surveyed.

The second module (B) has a box for inserting the name of the database to be accessed after pressing the “Load Data” button. This database must be stored in GeoPackage format (with a “.gpkg” extension). Since such type of file can store several layers, this front end was programmed for selecting the layer that is a homonym with the file name. Nevertheless, this programmer’s decision can be easily modified for introducing the name of the layer as well. This database (which has been initially set from the QGIS

environment, by using a dedicated Python-based script) contains a series of entries (buildings) and all the corresponding fields shown in the main module (parameters and sub-parameters of the VIM).

A limited selection of the database's fields is displayed in a table that can be scrolled down. After selecting a register from this table, the controls found in the main module will be set accordingly to the information contained in the respective entry. Some other relevant actions found in this module are:

- “Add New” button. It permits the addition of a new entry into the database. It is important to note that this new entry will not have geometrical or geographical information but can be later associated with a geometrical entity. It is critical to give an unused numerical key for any new entry;
- “Update”. This button will overwrite the entry associated with a given key with the data that has been set in the main module;
- “Reset”. This action cleans the main module, preparing it for performing writing actions;
- “Auto”. Once all the minimum parameters of the main module have been collected (i.e., excluding those in red colour), this button will execute all the calculations needed to obtain the rest of the parameters and, consequently, will calculate the vulnerability index and mean damage grades;
- “MQI Calc”. This capability calculates intervals for some mechanical properties of masonry panels by following the masonry quality index [30]. This calculator is independent of the VIM approach.

The third module (C) gives a short explanation of the results obtained when performing the VIM approach to have an interpretation of the expected damages by using automatically displayed short descriptive sentences based on the calculated levels of damage. Finally, the fourth module (D) includes both the parameters and results box for the MQI approach. The MQI assessment/evaluation was programmed as part of the survey, but its fulfilment is optional and does not condition the implementation of the VIM approach. It is considered an additional tool for performing quick assessments.

The input data for this module is based on the MQI evaluation and the results express the index values for the Vertical (MQI_V), In-Plane (MQI_I) and Out-of-Plane (MQI_O) assessments as well as the intervals for the mechanical properties proposed by Borri and De Maria [2015].

This software aims to facilitate the VIM processes for any stakeholder regardless of familiarity or knowledge of GIS databases, protecting the integrity of geographical data. This capacity would be especially useful for performing small editions or consults on large databases. The implementation of a small calculator for performing the Masonry Quality Index approach [Borri and De Maria, 2015] exemplifies the ability to design more comprehensive and enriched tools in an integrated environment that would embrace the assessment of concrete-based structures as well as other approaches of interest.

6.4.2 Remote access and edition.

Even if the database is locally created and stored (in the GIS environment), it becomes convenient to consider some advantages of remotely distributing it. To do so, for example, it may be suitable for disseminating the database among a group of trained professionals for covering different sections of a region while performing field work. This storage makes the database less sensitive to accidental losses due to local device malfunctions (inherently giving redundancy to the files) and facilitates data-sharing processes by the means of peer-to-peer communications (a direct user-to-user interaction) or public publishing.

WFS-T service.

It is important to consider that the use of adequate formats and data standards is key for successfully performing data sharing among different environments. In this sense, geographical databases are the object of several interfaces and frameworks that allow interoperability between different platforms and formats.

The Web Feature Service (WFS) of the Open Geospatial Consortium (OGC) is a standard interface for allowing requests for geographical features on web services based on the Geography Markup Language (GML) standard [Zheng et al., 2009]. The WFS standard enables the remote storage of GIS databases for being imported and even edited in local GIS platforms [Atzl et al., 2016]. Some platforms facilitate publishing layers on local or remote hosts.

As an example, the GeoServer open-source service enables interoperability for many standards [Růžička, 2016]. An inherent advantage of this service is its native implementation in numerous QGIS supplements. GeoServer enables access GIS layers by the means of web browsers but also to query the instances from GIS files as an online resource. This is another feasible strategy for distributing a comprehensive database among several actors that can perform individualised analysis maintaining the integrity of the original database.

WFS was used during the implementation herein presented for executing transactions (queries and updates) on remotely stored spatial data. The request is created for a local client (in this case, the QGIS local environment), so the WFS server reads and executes the request. There are basic operations that any WFS transaction must cover: obtain capabilities (indicate the feature types and the operations that support them), description of the feature type (for describing the structure of the feature type) and retrieving and fetching instantly information and properties upon client's request.

Additionally, the WFS operations can include the so-called transactional service (WFS-T), composed of operations that modify the features of the original database. Although GeoServer natively runs on a

local host address, it can be implemented on a virtual machine to work as a server, which is especially useful when taking advantage of the transactional WFS, which allowed querying and retrieving features with real-time synchronisation with the local QGIS environment.

Cloud-based distribution for mobile devices.

Another practical process is distributing GIS files for being consulted and edited on mobile devices. The app QField, for example, facilitates the edition of the attribute table of a GIS file by taking advantage of the geolocalisation of the mobile device [Ostadabbas et al., 2020]. This app, however, depends on the local storage of the file and implies the upload or download of the file for sharing it. An alternative service is provided by the Mergin [Dobias et al., 2021] cloud service. This cloud service has been implemented as a plug-in for QGIS and offers free (but limited) cloud-based storage. This storage permits the distribution of a complete functional QGIS file with other users, including the capability of editing the files from portable devices using the free app Input [Mizera et al., 2022] (Fig. 6.4).

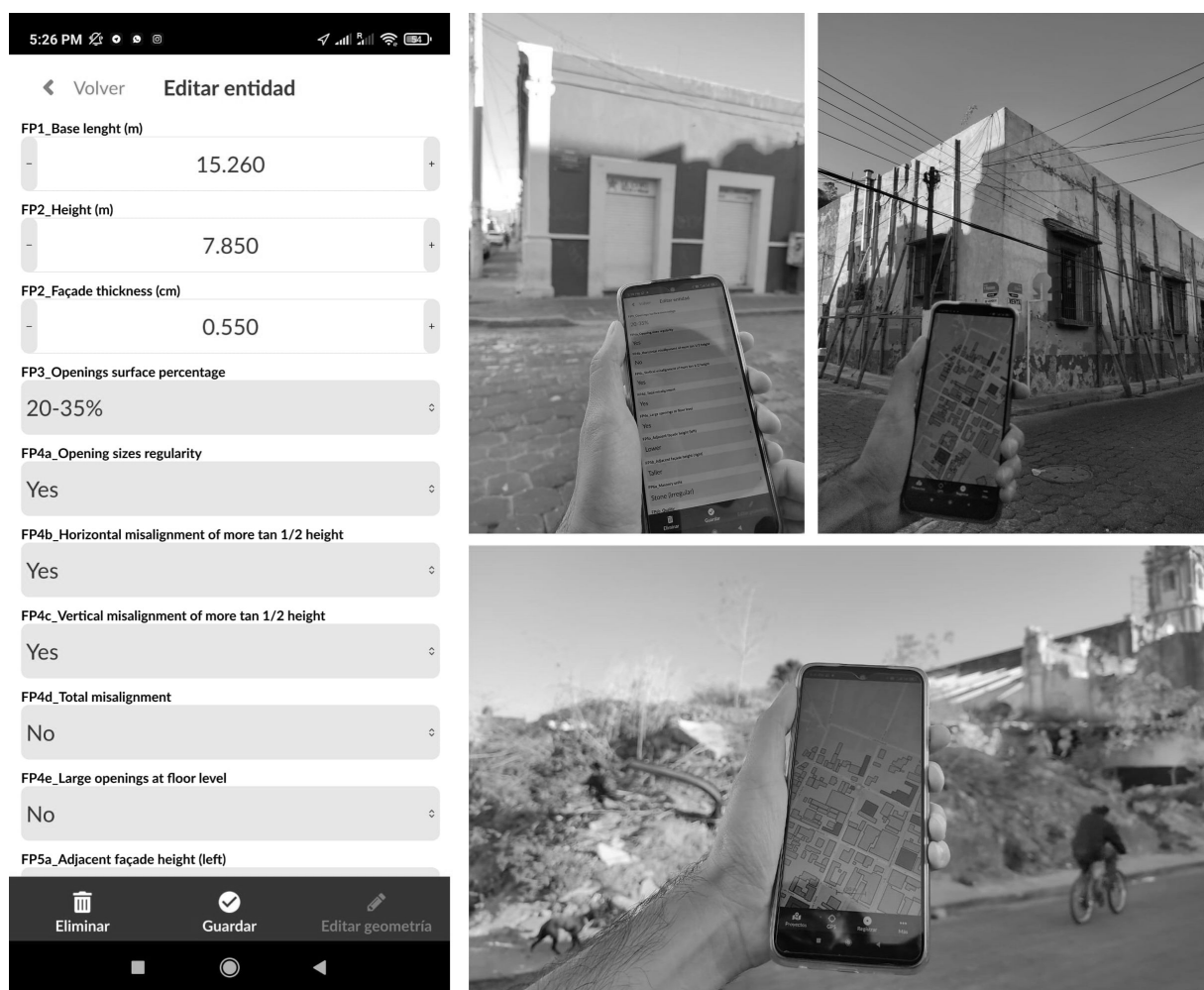


Figure 6.4: Example of the Input interface and its utilisation during on-site data acquisition.

This app also facilitates the addition of the attribute table and a real-time edition of the geographic layer, offering a convenient real-time synchronisation of the file throughout all devices. This last feature is especially meaningful for distributing files when working on teams and covering large areas. The capability of representing the fields as different types of input widgets (e.g., textboxes, number selections, multiple options, dial bars, checkboxes, etc.) facilitates the usability of this program for any user. Furthermore, it becomes possible to acquire attached fields, such as photographs or videos.

Examples of applications, such as the one described in Ramírez Eudave and Ferreira [2021a], have found that the joint use of QGIS-Mergin-Input is a feasible and robust framework for supporting field data acquisition campaigns. The databases distributed by these means, however, can also be shared without edition privileges, which may be significant for sharing information that is produced or managed in a more centralised way.

6.5 Outcomes and potential use for mitigating damage and losses.

The data acquisition process for a determinate urban environment may involve many of the strategies described for achieving the parametric description of all the considered constructions. The calculation of the vulnerability index of the buildings can be easily obtained by using the Seismic Vulnerability Calculator, including the results in the database as well. The vulnerability index of a set of constructions is easily representable by using straightforward maps from QGIS, for example. These maps represent thresholds for the vulnerability of buildings, intuitively providing a base for identifying the most sensitive elements of a determined city.

The use of the Seismic Vulnerability Calculator software also facilitates the obtention of damage grades for the set of constructions, given a certain macroseismic intensity and the structure's ductility. This process is intended to be more flexible and direct than operating the QGIS file, for example. The outcomes permit highlighting those constructions that are more likely to fail or suffer damage when facing a certain scenario. This semi-quantitative information is of great value for numerous stakeholders that have a decision tool for prioritising interventions and immediate actions that can also consider some aspects that are not contained in the VIM approach but can be mapped on the GIS database: social vulnerabilities, number of users, economic indicators, cultural values, protection status, etc. Furthermore, the calculation of damage grades would be the basis for more complex urban-level analysis. It is possible to build a damage curve for the constructions since the levels of damage ($\mu_D = 0 : 5$) are a function of the vulnerability (V)

and the macroseismic intensity I_{EMS98} as expressed in Equations (6.4) and (6.5). For example, Figure 6.5 shows a series of outcomes from a building in the city of Atlixco (Puebla, México).

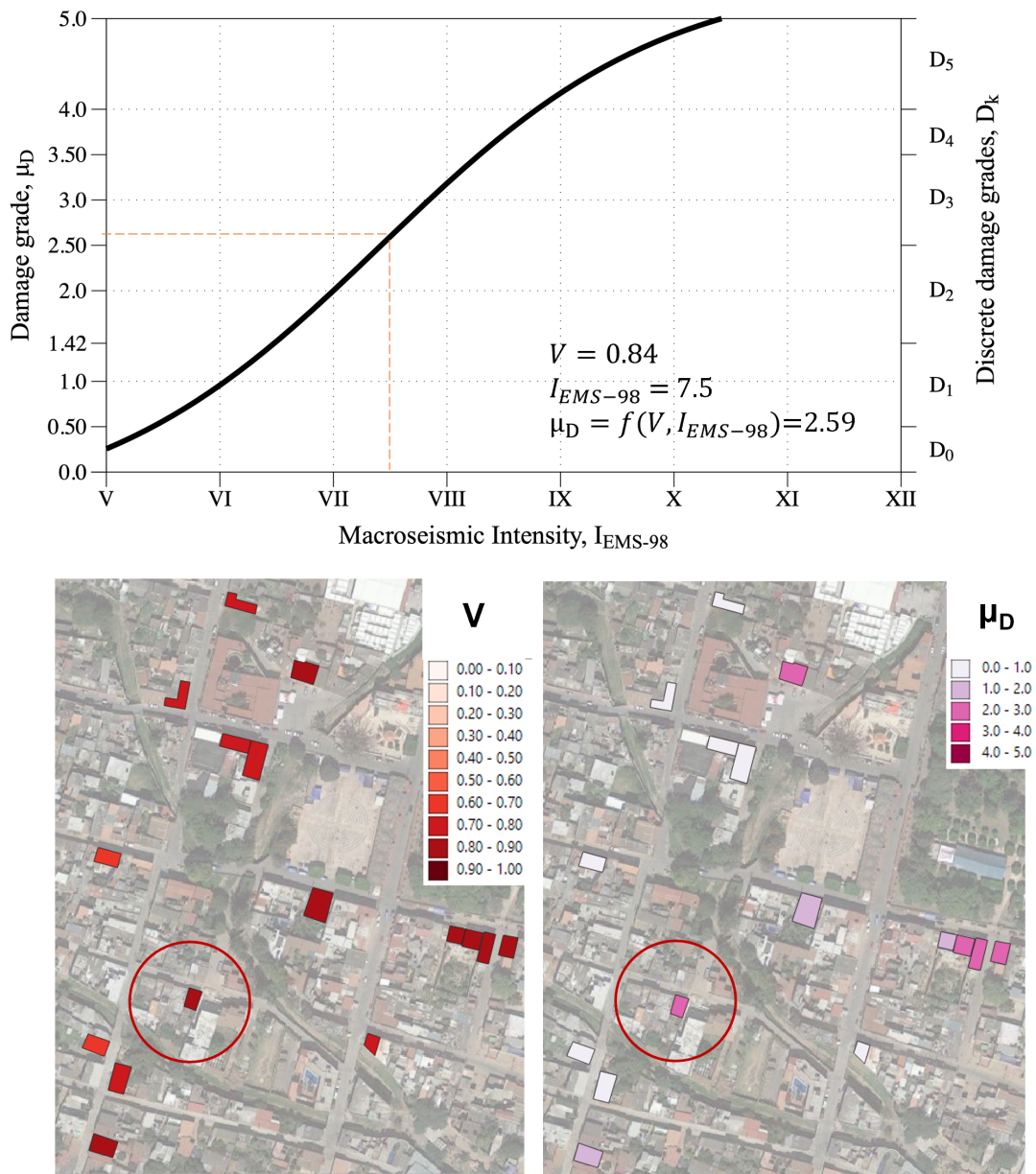


Figure 6.5: Damage curve based on the values obtained from the seismic vulnerability calculator (top) and visual representation of the levels of vulnerability V and mean damage grade μ_D by using the GIS environment (bottom).

The vulnerability value (V) obtained by the means of the Seismic Vulnerability Calculator is used for feeding Equation (6.4), which permits the construction of a damage/macroseismic intensity function curve. This analytical value can be displayed in specific maps by using the QGIS environment, facilitating the generation of outcomes in which the level of vulnerability or the level of damage (given a determined macroseismic intensity) is reflected.

Hence, given a certain seismic intensity, it becomes feasible to anticipate levels of damage throughout the sample, identifying which constructions are more likely to have severe damage or even complete failures. The activation of total or partial failures due to out-of-plane mechanisms would imply a partial obstruction of certain streets or communications because of the accumulation of debris, which is relevant for emergency planning actions and evacuation plans.

In addition to collapses, the thresholds of unusability of constructions are relevant indicators for anticipating the loss of urban critical functions (commerce, housing, health, education services, etc.), favouring nominal life estimates based on the return periods associated with certain seismic intensities. Hence, this information is a relevant element for performing long-term urban planning and for anticipating the most vulnerable systems of a certain urban settlement. The risk analysis of the city based on the loss or interruption of some of its functions [Ramírez Eudave and Ferreira, 2021e] is also very compatible with the workflow herein presented.

It is important to recall, however, that the elements considered for this workflow are also intended to offer a flexible and user-friendly environment for updating and/or correcting data, which implies the possibility of having up-to-date outcomes, including updates on the city (for example, when a better knowledge of a certain construction is available) or in the seismic vulnerability approach (for example, when calibrated after a seismic event).

6.6 Final Remarks.

This chapter discusses the suitability of using a parameter-based seismic vulnerability assessment approach to carry out large-scale vulnerability assessments in the context of historical cities. Furthermore, the feasibility and convenience of implementing the entire workflow on geodatabases are discussed, focusing on the open-source GIS software QGIS. In addition to supporting this implementation, the suitability of using complementary approaches and tools is herein presented and explored.

Firstly, the possibility of developing and implementing a Python-language-based software for reading, managing, and editing GIS layers is explored. This would not only facilitate the management of geodatabases outside of GIS environments but would also offer a user-friendly interface for collecting core and complementary input data for the methodology and a semi-automatic calculator for obtaining the vulnerability index and mean damage grade results.

Secondly, two alternatives for the remote distribution of GIS databases are presented and discussed. The use of the WFS-T protocol is a valuable resource for publishing GIS layers that can be locally consulted

and edited. On the other hand, using cloud-based tools opens the possibility of distributing GIS data on several devices with reading and writing privileges. This capability is highly relevant for performing field campaigns involving many actors and can have an almost immediate synchronisation, minimising the time invested in data treatment. Both approaches represent strategies for implementing a free, enlargeable and potentially online system for data acquisition, treatment and representation of the seismic vulnerability of constructions. Some alternatives that are a matter of future research are browser-based front ends for online database services.

Finally, some relevant uses of the outcomes of the VIM–GIS implementation are discussed. The generation of vulnerability maps is a valuable tool for representing the overall vulnerability state of a city or certain regions. Furthermore, the damage curves are the base for anticipating damage and loss scenarios given a determined seismic intensity, which might reasonably impact the design of emergency planning and nominal-life-oriented urban decisions aimed to mitigate the negative impacts of earthquakes.

Chapter 7

Calibrating a vulnerability model with Machine-Learning and observed damages.

General objectives		Subtopics		Chapters	
1. Descriptive models.	2. Data acquisition.	Remote-sensing surveying, GIS, BIM and HBIM integration for urban-scale surveying.		2	3
		Semantic description of the Historic Urban Landscape.			
		Comprehensive HUL-oriented databases.			
		Seismic Vulnerability Index Method survey.		4	5
	3. Data framework and management.	Mexican Catalogue of Historical Monuments			7
		Large-scale implementation.			
	4. Seismic vulnerability assessment.	In situ surveying with digital tools.			6
		GIS databases setup and distribution.			
		Seismic Vulnerability Calculator software.			
		Calibration by the means of Machine Learning algorithms.			

Rafael Ramírez Eudave, Tiago Miguel Ferreira, Romeu Vicente, Paulo B. Lourenco and Fernando Peña (2023) *Parametric and Machine Learning-Based Analysis of the Seismic Vulnerability of Adobe Historical Buildings Damaged After the September 2017 Mexico Earthquakes*, *International Journal of Architectural Heritage*. DOI: 10.1080/15583058.2023.2200739

Abstract.

In September 2017, two strong earthquakes hit the central region of Mexico, producing substantial damage to the historical buildings. A retroactive analysis for assessing the pre-event seismic vulnerability of these constructions allowed for testing the suitability of an existing parameter-based approach based on material and geometrical features. More than 160 adobe buildings in four municipalities of the State of Morelos were visited, surveyed and included in a straightforward vulnerability-oriented Geographical Information System (GIS) database. Data were collected on-site and managed by resorting to open-source GIS software combined with a Python-based database management tool and a cloud-based platform for onsite data collection using mobile devices. The parameter-based approach was used for assessing the analytical seismic vulnerability of the buildings and implementing a secondary, more conservative assessment that considers the data acquisition-related uncertainties and limitations during the field works. The capabilities of the database were further used to train a Machine Learning algorithm with the objective of overcoming some representativeness limitations of the parameter-based analytical method. This third approach was found to be suitable to assess the vulnerability of the building typologies addressed in this investigation. Despite the implementation discussed in this paper is limited to a specific vernacular typology, it can be used to conduct customised local calibrations based on a more general vulnerability survey.

7.1 Introduction.

According to the United Nations International Strategy for Disaster Reduction [United Nations Office for Disaster Risk Reduction, 2017], vulnerability is defined as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard”. Assessing the seismic vulnerability of the existing building stock is critical to the definition and implementation of proactive and reactive seismic risk mitigation actions. Nevertheless, the evaluation of large numbers of buildings poses numerous challenges related to the heterogeneity among existing constructions. This aspect is more explicit when dealing with historical buildings, typically subjected to many sources of uncertainty. Some common analytical strategies may be unsuitable for performing fast and reliable structural analysis at the urban scale (e.g., structural analysis based on numerical models), bringing attention to more empirical approaches based on the identification of characteristics that seem to enhance the seismic performance of structures.

A relevant precedent of this approach for Reinforced Concrete buildings has been developed by Ruggieri et al. [2022], combining a typological classification of structures with a series of standard numerical models for building fragility curves. In this case, the data extraction is aided by Machine Learning algorithms, which label each building according to a series of externally recognisable features. This tool, known in the literature as Vulnerability Analysis using Machine Learning (VULMA) [Ruggieri et al., 2021], is composed of a series of modules that recognise typological patterns from raw data, including pictures. This process is possible given expert judgement-based training in which a series of categories are manually assigned. Although the need for fulfilling some typological assumptions constrains the application of this approach, it was found suitable for assessing large sets of constructions.

In the case of unreinforced masonry constructions, the approach developed by Rosti et al. [2021] builds up on a preliminary categorisation based on the classifications created after the Irpinia (1980) and L'Aquila (2009) earthquakes for building statistical distributions to get a set of relevant typological features that are then compared against the observed levels of damage. By following this approach, the authors have derived a set of empirical fragility curves representative of the seismic vulnerability of typologically compatible buildings. This knowledge, based on long-term observations of failure and success, has determined construction traditions and vernacular architecture principles worldwide. It is worth noting that the development of these empirical processes is not substantially different to the training of computational algorithms, in which a series of existing incomes and outcomes are analysed to find patterns and relations for predicting the outcome of new income data.

7.1.1 The Earthquakes of September 2017 in Mexico.

On the 7th of September 2017, an earthquake ($M_W = 8.2$) hit the south coast of Mexico. This event, later known as the Tehuantepec Earthquake, had its origin 133 km southwest of Pijijiapan (State of Chiapas).

There was extensive damage in the building stock, namely in adobe and unreinforced masonry structures in the states of Oaxaca and Chiapas [Godínez et al., 2019]. On the 19th of September 2017, the so-called Puebla-Morelos Earthquake ($M_W = 7.1$) hit the south centre of the country (Figure 7.1).

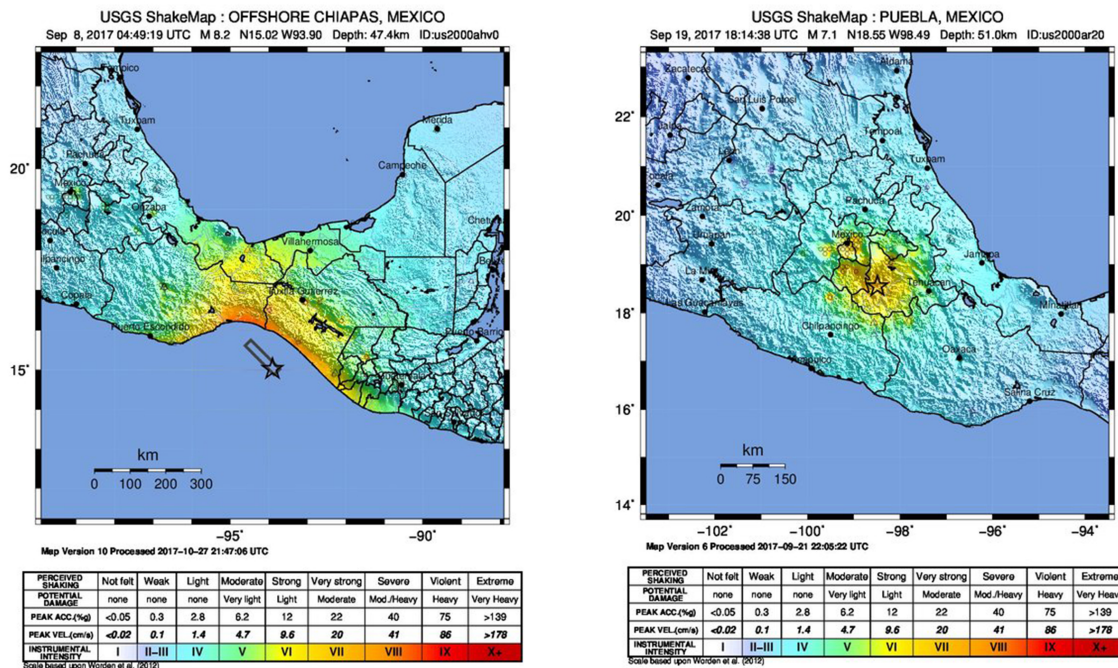


Figure 7.1: USGS Shake maps for the Pijijiapan (left) and Puebla-Morelos (right) Earthquakes [Geodetic Facility for the Advancement of Geoscience, 2023].

This event had its epicentre 12 km southeast Axochiapan (State of Morelos), ca. 120 km away from Mexico City, producing the collapse of at least 46 structures in the capital [Alberto et al., 2018] [Buendia and Reinoso, 2019]. Both events left behind a large number of houses with medium and severe damage in the central and southern regions of the country, see Table 7.1.

7.1.2 Impact and losses of historical buildings.

According to the Global Assessment Report of Disaster Risk Reduction Atlas [UNISDR - United Nations Office for Disaster Risk Reduction, 2017], seismic events in Mexico are responsible for annual average losses ranging between 1,001 and 2,000 million USD. The figures for the 2017 events are even more significant, with estimated reparations costs reaching between 2,000 and 4,500 million USD due to ca. 180,000 affected houses (ca. of 0.56% of the total of housing units registered in the national census).

State	Housing units	
	Damaged	Full damage
State of Mexico	6059	2468
Mexico City	5765	2273
Morelos	15352	1323
Puebla	27812	3214
Oaxaca	63336	21823
Chiapas	59397	18058
Tlaxcala	34	0
Guerrero	2976	1451

Table 7.1: Affected housing units per State as result of the Earthquakes of the 7th and 19th September, 2017 [Senado de la Republica, 2017].

States like Oaxaca (6.07%), Chiapas (4.71%) and Puebla (1.79%) have been particularly affected, with around 6%, 5% and 2% of their buildings stocks, respectively, heavily affected by the quake Caprano et al. [2018], Ramírez Eudave et al. [2022]. The Mexican Civil Protection authority [Senado de la Republica, 2017] estimated 369 human losses and 180.731 damaged houses (from which a 28% was reported as total loss). In the context of cultural architectonic heritage, the Mexican Secretary of Culture estimated that some 2340 historical monuments were affected, including 1,680 temples built before 1900 [Lara Gutiérrez, 2017]. Nevertheless, the number of damaged historical housing units is still unknown. These ancient houses are particularly significant in the states of Morelos and Puebla (commonly built in adobe), in which damages were proportionally more extensive [Galvis et al., 2017].

Adobe structures in Morelos represent ca. 4.5% of housing units [Sánchez Calvillo et al., 2021] reaching proportions of more than 20% in other municipalities [INEGI - Instituto Nacional de Estadística y Geografía, 2023]. The development of a vernacular tradition of adobe structures in this region is closely link to the occurrence of seismic events, shaping specific and adapted building typologies [Guerrero Baca, 2019]. The scale of damages in several settlements after the Puebla-Morelos earthquake urged immediate intervention due to the humanitarian crisis derived from the collapses and the lack of services, being declared as disaster zones Caprano et al. [2018].

A relatively common reaction to the loss or damage of adobe-based buildings was their replacement with new houses by using more industrialised building systems and technology, including prefabricated modules. This process is the product of one or several of the following situations (stated by the testimonials gathered during the fieldwork phase of this work):

- There is a perception of adobe-based constructions as inherently dangerous and vulnerable towards seismic actions. This perception was reinforced after several official statements from the Mexican

government [Zatarain, 2017].

- Adobe houses are perceived as outdated for some contemporary needs.
- There is a lack of good workmanship and artisans for repairing and replicating the ancient construction techniques, and, therefore, quality work for adobe construction is often expensive when compared with more recent construction processes and technology.
- In many cases, access to public or private funds for reconstruction was subjected to the acceptance of architectonic criteria and features with no participation or intervention of the habitats and/or owners. Among others, the urgency to recover and rebuild after the seismic events leads to accepting these conditions.
- Some owners had to invest their resources in reconstruction. These resources, often very limited, were insufficient for developing a proper architectural and engineering project, making their buildings less prone to earthquake actions.

Therefore, this substitution process was accompanied by the demolition of historical structures and even buildings that could be subjected to retrofitting and strengthening actions. Furthermore, the retrofitting and/or strengthening of adobe structures were perceived as more costly and relatively useless when compared to building new structures.

This loss of cultural heritage represents a long-term impact to the detriment of both tangible and intangible assets (these constructions are the materialisation of the accumulated knowledge of several generations). Moreover, this loss represents a hazard for sustaining long-term consolidated economic dynamics, such as the touristic attractiveness of some historical centres. As stated in the Historic Urban Landscape (HUL) guidelines [UNESCO, 2016], the conservation of these environments is especially meaningful given the permanent nature of the loss of historical assets. For example, the municipality of Tepoztlán (State of Morelos) is very illustrative: the integration of landscape, urban and historical architecture sustains strong cultural and eco-touristic activities that represent the main local economic activity [Alvarado Rosas, 2015].

The study herein presented is aimed to explore assessment strategies for proactively identifying vulnerable constructions, admitting that prevention is preferable to reparation and substitution. This task is inscribed in some international guidelines, such as the Chart of the Sendai Framework for Disaster Risk Reduction 2015-2030 [United Nations General Assembly, 2015], whose first urgent action is “Understanding Risk”, including pre-disaster risk assessments.

Furthermore, according to the "Geoethics" principles, [Peppoloni and Di Capua, 2021], the awareness of potential risk situations is key to having successful public policies and represent a professional responsibility for developing better practices involving a more robust social role. Hence, the vulnerability assessment of historical constructions is complementary to cultural and economic sustainability and an opportunity for a more informed and participative decision-making process towards risk mitigation.

7.1.3 Outline of this study.

This work's first step is based on the use of a seismic vulnerability assessment approach extensively applied in European historical cities for analysing some Mexican built environments. This approach, developed from the Italian GNDT-II method [Gruppo Nazionale per la Difesa dai Terremoti—GNDT, 1994], is based on the retroactive identification of material, physical and geometrical parameters that seem to influence the seismic behaviour of masonry constructions. Therefore, the evidence of seismic events in the last three decades allowed us to enhance, enrich and adapt this approach, leading to different variations and calibration of parameters for different regions and several cities.

For this method's purposes, the descriptive model of constructions considers a total of 14 parameters drawn from a straightforward survey. The first insight for applying this method was explored in the city of Atlixco, Puebla, finding the suitability of using the Mexican Catalogue of Historical Monuments for feeding the aforementioned survey [Ramírez Eudave and Ferreira, 2021d]. Nevertheless, some limitations related to the uncertainties during data acquisition were found. A second experience with more than eighty buildings [Ramírez Eudave et al., 2022] allowed having a better understanding of the suitability of this approach, its limitations and its possibilities.

The present study is aimed to explore the suitability of this method on a different Mexican traditional typology (that of adobe-based structures), based on the comparison between the levels of physical damage predicted by the method against the real effects, this is the observed physical damage that the 2017 Earthquake had, feeding a discussion about the representativeness of the vulnerability-oriented model and the studied built environment. Despite the VIM approach being mostly applied to stone or brick masonry constructions, the version adopted for this study [Ramírez Eudave et al., 2022] explicitly accepts the suitability of assessing adobe-based constructions without performing specific calibrations. This capability of the parametric method is possible since adobe is part of the vulnerability classes defined and typified in the EMS-98 approach [Vicente, 2008].

Given that we accept that the set of parameters is representative for conditioning the level of damage, it is possible to accept it as a Handcrafted Feature Extraction Technique [Dash et al., 2022]. This means

that a series of features that can be extracted from a certain element (in this case, buildings) are valuable for predicting a certain phenomenon (such as seismic structural response). Therefore, it is possible to use this methodology as a base for training a Machine Learning algorithm to recognise potential different configurations of the vulnerability-oriented survey that better represent this sample, leading to a new potential use of the parameter-based methodology.

7.2 Materials and methods.

This work was performed by following a series of field surveying campaigns in four different municipalities of the State of Morelos: Jojutla, Tepoztlán, Tlayacapan and Yautepec, in which there exists a complete and relatively updated Catalogue of Historical Monuments [INAH, 2019]. This research is aimed to compare the level of damage that the structures had in the context of two different approaches for predicting it: a parametric vulnerability index approach (considering both, a direct and a range-based application for addressing some epistemic uncertainties) and a machine learning algorithm for finding a more suitable model based on the method's survey.

7.2.1 Vulnerability Index Method (VIM): parameters and procedure.

The version of the Vulnerability Index Method (VIM) herein used coincides with the one reported for Atlixco, Puebla [Ramírez Eudave et al., 2022], in which the criteria for grading the parameters are extensively reported. Each parameter (see Table 7.2) is graduated in four different growing vulnerability classes (A, B, C, D) that represent how negative a given configuration is for the overall behaviour of the structure. Each grade is later associated with a numeric value C_{vi} that is later multiplied by the parameter's weight p_i (a numerical representation of the relative relevance that the parameter has among the set of all parameters) in order to obtain a weighted sum of all parameters as a global vulnerability index I_{vf}^* as per Equation (7.1), , later normalised for obtaining a vulnerability value V (Equations (7.2) and (7.3)).

An approach for estimating the damage grade $\mu_D = 0 : 5$ given a certain seismic intensity is given in Equation (7.4). This expression includes a ductility factor for the structure $Q = 1 : 4$ and represents a damage curve in which the macroseismic intensity is associated with a damage grade μ_D , conceptually framed in the EMS-98 system [Centre Européen de Géodynamique et de Séismologie, 1998]. A correction for the vulnerability is given in Equation (7.5) for macroseismic intensities below 7.

Parameters	Class C_{vi}				Weight p_i	Relative weight
	A	B	C	D		
Group 1 Structural building system						50/100
BP1. Type of the resisting system	0	5	20	50	2.50	
BP2. Quality of the resisting system	0	5	20	50	2.50	
BP3. Conventional strength	0	5	20	50	1.00	
BP4. Maximum distance between the walls	0	5	20	50	0.50	
BP5. Number of floors	0	5	20	50	0.50	
BP6. Location and soil condition	0	5	20	50	0.50	
Group 2 Irregularities and interaction						20/100
BP7. Aggregate position and interaction	0	5	20	50	1.50	
BP8. Plan configuration	0	5	20	50	0.50	
BP9. Height regularity	0	5	20	50	0.50	
BP10. Wall façade openings and alignment	0	5	20	50	0.50	
Group 3 Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	
BP12. Roofing system	0	5	20	50	2.00	
Group 4 Conservation status and other elements						12/100
BP13. Fragilities and conservation status	0	5	20	50	1.00	
BP14. Non-structural elements	0	5	20	50	0.75	

Table 7.2: Vulnerability Index parameters, according to the calibration of Ferreira et al. [2017c].

$$I_{vf}^* = \sum_{i=1}^{14} c_{vi} p_i \quad (7.1)$$

$$I_v = \frac{I_v^* \times 100}{750} \quad (7.2)$$

$$V = 0.592 + 0.0057 \times I_v \quad (7.3)$$

$$\mu_D = \left[2.5 + 3 \times \tanh \left(\frac{I_{EMS-98} + 6.25 \times V - 12.7}{Q} \right) \right] \times f(V, I); 0 \leq \mu_D \leq \quad (7.4)$$

$$f(V, I) = \begin{cases} \frac{V}{e^{(2 \times I - 7)}} & \text{for } I \leq 7 \\ 1 & \text{for } I > 7 \end{cases} \quad (7.5)$$

A critical aspect of this approach is the correspondence between the mean damage grade μ_D and a set of discrete damage grades D_K , qualitatively characterised according to the macroscopic observed evidence of damage, as shown in Table 7.3. The VIM method was implemented for calculating the levels of damage that would theoretically correspond to the studied buildings when facing a seismic event with the intensity of the Puebla-Morelos earthquake (i.e., for obtaining values for μ_D).

Discrete damage grades, D_k	Range for μ_D	
	μ_D^-	μ_D^+
D_0 —No damage. No observed damage	0.00	0.50
D_1 —Slight damage. Presence of very localised and hairline cracking	0.50	1.42
D_2 —Moderate damage. Cracking around openings; localised detachment of wall coverings (plaster, tiles, etc.)	1.42	2.50
D_3 —Severe damage. Opening of large diagonal cracks; significant cracking of parapets; masonry walls may exhibit visible separation from diaphragms; generalised plaster detachment	2.50	3.50
D_4 —Very severe damage. Façade walls with large areas of openings have suffered extensive cracking. Partial collapse of the façade (shear cracking, disaggregation, etc.)	3.50	4.00
D_5 —Destruction. Total in-plane or out-of-plane failure of the façade wall	4.00	5.00

Table 7.3: Correspondence between discrete damage grades and ranges of mean damage grade.

The correlation between D_k and μ_D later permitted the comparison between the levels of damage obtained from the VIM approach against the real observed consequences (D_k) that the September 2017 Earthquake had on the assessed structures. For this purpose, the intensity information (in MMI scale) from the United States Geological Service was consulted [United States Geological Survey USGS, 2017]. The intensity maps for this earthquake lead to take an intensity $M_w = 7$ for the municipality of Jojutla, $M_w = 7.1$ for Tepoztlán and $M_w = 7.3$ for Yau-tepec and Tlayacapan [Sahakian et al., 2018]. The ductility of all the structures herein analysed was based on the recommendations of the Complementary Technical Code for Seismic Design of the Building for Mexico City [Gobierno del Distrito Federal, 2017], which is the reference for most of the country. This code recommends a value of $Q = 1$ for unreinforced masonry.

7.2.2 Data management and acquisition framework.

A Geographic Information System environment was used for storing and managing the data of this study, given the advantages of having a geographic reference for identifying each construction during the on-site campaign. The open-code and free software QGIS (version 3.12 Bucureşti) [QGIS Development Team, 2021] was selected for this purpose. A convenient capability of using QGIS for assembling the database was the use of the plug-in Mergin [Dobias et al., 2021], a cloud-based storage service that allows the

access and edition of the QGIS file from multiple mobile devices, such as smartphones equipped with the app Input [Ramirez Eudave et al., 2022a].

The survey was programmed as an attribute table for the layers that would later store the polygons corresponding to the constructions, containing a total of 68 fields for storing field data and assessment results (see Table 7.4), including qualitative, quantitative and Boolean data. Besides having this geographic database as a Geopackage file, a python-based front-end was programmed for performing reading and edition actions on the database. This front-end component integrates the possibility of calculating the vulnerability index and the levels of damage based on the parameters stored in the GIS database. The purpose of this script is to facilitate data management and calculations while keeping the integrity of the primary database (see Figure 7.2).

Type of fields	Fields	Notes
Identification	2	Address and unique key.
Building parameters	41	Geometrical and material features considered for the grading the parameters of the VIM.
Seismic parameters	1	Seismic intensity in EMS-98 scale.
Quality Check	14	Index for grading the level of uncertainty related to each parameter.
Results	10	Storage of the vulnerability index, intermediate and final results.
Total	68	

Table 7.4: General composition of the QGIS layer attribute table.

Seismic Vulnerability Calculator v. 1.2 (12/21)

Building Key: 1.0 Search Address: Alameda Unive 5 QC Help

Conservation: Regula More 0a.Type of masonry: B More

0d.Height: 6.35 More 0b.Type of diaphragm: C More

0e.Storeys: 2 More 0c.Roofing system: A More

0f.Facade_a: 17.5 More BP1_Type and org. res. syst.: A More QC1: A

0g.Facade_b: 23.65 More BP2_Quality resisting syst.: C More QC2: A

0h.Facade_s: 0.85 More BP3_Conventional strength: B More QC3: B

3a.W_Area_x: 1123.5 More BP4_Max. dist. walls: A More QC4: B

3b.W_Area_y: 1365.2 More BP5_Number of floors: B More QC5: B

3c.W_Area_t: 2456.2 More BP6_Soil conditions: B More QC6: A

3d.L_Span_P: 3.65 More BP7_Aggregate position: B More QC7: A

3e.tau_k: 50 More BP8_Plan configuration: D More QC8: C

3f.p_m: 24 More BP9_Height regularity: A More QC9: A

3g.L_w: 4.5 More BP10_Openings: alignment: A More QC10: A

3h.p_s: 3 More BP11_Qty. Horiz. Diaph.: C More QC11: B

6a.Soil: A More BP12_Roofing System: B More QC12: A

6b.Slope: B More BP13_Conserv. State: A More QC13: A

6c.Delta_h: B More BP14_Non-struct. elem.: B More QC14: B

6d.Foundation: Y More Ductility of Masonry - Q: 2 MMI: 7.5

8a.Plan (a): 14.95 More I_vf: 111.25 I_vf_c: 111.25

8b.Plan (b): 8.5 More I_v: 17.12 I_v_c: 17.12

12a.Roof thrust: A More V: 0.69 V_c: 0.69

12b.Perim. reinf.: Y More Mu_d: 1.92 Mu_d_c: 1.92

Geopackage file: Master Load data About Exit

Parameters in RED can be automatically obtained having all those in BLACK fulfilled
The vulnerability index can be automatically calculated having all BLACK and RED parameters
Read the Quality Check Help (QC Help) for obtaining a conservative approach based on uncertainty

Add new Update Reset AUTO MQI CALC

Key	Address	I_vf	I_v	V	Q	Mu_d	I_vf_c	I_v_c	V_c	Mu_d_c
1.0	Alameda Unive 5	111.25	17.12	0.69	2	1.92	111.25	17.12	0.69	1.92
2.0	Capt Alfredo Guir	293.7	45.19	0.85	2	2.96	293.7	45.19	0.85	2.96
3.0	Vasco da Gama 6	173.7	26.73	0.74	2	2.27	173.7	26.73	0.74	2.27

Suggested grades according to the given data: BP2: C BP3: B BP4: A BP6: B BP8: D BP12: B
Regular: I_vf=173.75 I_v=26.73 V=0.74 Mu_d= 2.27/5.00 for the given ductility and Seismic intensity
Expected damage D2: Moderate. Cracking aroun openings, local detachment of plasters
Conservative: I_vf=173.75 I_v=26.73 V=0.74 Mu_d= 2.27/5.00 for the given ductility and Seismic intensity
Expected damage D2: Moderate. Cracking aroun openings, local detachment of plasters

F	About	SM Mech. prop. and cons. state	MQI_V	MQI_I	MQI_O
F	About	SD Stone/brick dim. properties	5.6	4.9	4.9
PF	About	SS Stone/brick shape	Min	Mean	Max
PF	About	WC Wall leaf connections	0	0	0
F	About	HJ Horizontal bed joints	0	0	0
PF	About	VJ Vertical bed joints	0	0	0
F	About	MM Mortar properties	0	0	0
Y	About	Thick bed joints	0	0	0

Figure 7.2: Screenshot of the python-based front-end.

7.2.3 Characterisation of the sample and field surveying.

Given the affinity of the National Catalogue of Historical Monuments regarding the parameters considered in the VIM, those municipalities with the larger samples of catalogued buildings were selected. Among these municipalities, those whose entries in the Catalogue were completely fulfilled were preferred: Jojutla, Tepoztlán, Tlayapacan and Yautepec. It is important to note that only constructions destined to housing were considered for this study, discarding other historical structures such as churches, agricultural complexes or other industrial facilities. Although the presence of adobe constructions in these municipalities is variate (Table 7.5), the assets considered in the National Catalogue of Historical Monuments (i.e., constructions built before the year 1900) are predominantly adobe-based constructions.

Municipality	Number of housing units	Adobe-based housing units	Proportion
Jojutla	3705	83	2.24%
Tepoztlán	3866	423	10.94%
Tlayacapan	2246	451	20.08%
Yautepec	3927	95	2.42%
Total	13744	1052	7.65%

Table 7.5: General description of the housing environment for the studied municipalities according to the Census of 2014 [INEGI - Instituto Nacional de Estadística y Geografía, 2023].

An original indicative list of 198 constructions was prepared, as shown in Table 7.6. These constructions were visited to perform visual inspections to accomplish the vulnerability survey and correct any outdated information from the National Catalogue of Historical Monuments (NCHM). This campaign led to the exclusion of several constructions (for example, some buildings were inexistent or structurally heavily modified when the earthquake hit) profiling a final universe of 167 valid cases that were characterised, stored and analysed.

Municipality	Indicative list	Effective records	Percentage
Jojutla	68	55	80.89%
Tlayacapan	34	33	97.06%
Yautepec	49	42	85.71%
Tepoztlán	47	37	78.72%
Total	198	167	84.34%

Table 7.6: Number of constructions considered per municipality.

The fieldwork allowed the accomplishment of a series of activities:

- Visual confirmation of the descriptive information contained in the National Catalogue of Historical Monuments. The position of the construction was confirmed or corrected. Then, the information

contained in the Catalogue was compared against the field data gathered, leading to corrections, if necessary.

- Photographic register of the interior and exterior. All constructions were at least registered by the exterior. In many cases, access was not allowed or restricted. When access was not permitted, the interior description of the constructions was based on the content of the National Catalogue of Historical Monuments. It is convenient to recall that only buildings with a complete datasheet (i.e., with architectonic floor plan, photographs and descriptions) were considered valid samples during the preliminary selection.
- Damage questionnaire to the owners/users of the constructions. Besides communicating the goal and procedure of the fieldwork, the users were asked to describe the type of damage that structures had after the 2017 Earthquakes. The diagram that illustrates the classification of damage to masonry buildings in the EMS-98 scale [Centre Européen de Géodynamique et de Séismologie, 1998] was shown to better classify the level of damage (see Figure 7.3).
- Geometrical measurements (e.g., exterior measures for contextualising the architectonic plan drawing of the Catalogue).
- Register of information for grading vulnerability index parameters.

Many of the fields were able to be directly registered on-site by using the app “Input” for editing the GIS database. In some cases, quantitative vulnerability index parameters were able to be graded only after performing some calculations, assisted by the python-based front end.

The vernacular typologies found in these municipalities are common to most of the State of Morelos and present little variations Meraz Quintana Leonardo, Guerrero Baca Luis [2010]. These houses commonly consist of a single-storey level (ground) room with a rectangular plan configuration for rural areas, whilst urban houses present a series of rooms of similar sizes, internally connected and aligned with the street (see Figure 7.4).

The most common structural solution is one-leaf adobe walls built with units of ca. 52cm in length, 36cm in width and 9cm in thickness. Although there are no additional means of reinforcement or strengthening, there is good interlocking and layering and most constructions have visible stone foundations. Most foundations reach a height of between 0.50 to 1.00m from the level of the street, mainly as a strategy for isolating the adobe walls from the soil humidity and rainwater (see Figure 7.5). The most common roof solution is a plane-pitched roof that facilitates rainwater collection by the means of dedicated ceramic pipes. The openings in these constructions are proportionally small, solved by means of timber lintels or stilted arches.



Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage).

Hair-line cracks in very few walls.
Fall of small pieces of plaster only.
Fall of loose stones from upper parts of buildings in few cases.



Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage).

Large and extensive cracks in most walls.
Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).



Grade 5: Destruction (very heavy structural damage)

Total or near total collapse.



Grade 2: Moderate damage (slight structural damage, moderate non-structural damage).

Cracks in many walls.
Fall of fairly large pieces of plaster.
Partial collapse of chimneys.



Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage).

Serious failure of walls; partial structural failure of roofs/floors.

Figure 7.3: EMS-98 five damage grade scale [Centre Européen de Géodynamique et de Séismologie, 1998] and examples of buildings with corresponding damage grades from 1 to 5 in the studied municipalities.



Figure 7.4: Examples of urban (left) and rural (right) houses.

Although there is a certain variability throughout the sample, most of the assessed constructions (see Figure 7.5). share several characteristics.



Figure 7.5: Typologically representative constructions from the municipality of Tepoztlán.

The adobe walls present earth-mortar joints in which small ceramic pieces or stones are embedded to offer better protection (see Figure 7.6). The adobe units are visibly homogeneous, and only two elements are easily recognisable: the earth matrix and fine vegetal fibre elements.

All the local inhabitants that were inquired about the typical constitution of adobe bricks described the production of adobe from a mixture of the soil available onsite and horse manure that is compressed



Figure 7.6: Typical adobe configuration in a house in the municipality of Tlayacapan.

in wooden formworks and sun-dried. Even if many of the constructions have no external render, the inhabitants often state that this is a relatively recent tendency, mostly for offering an attractive “rural” visual landscape for tourism purposes.

The physical damage of the number of structures assessed was classified as per the EMS98 scale and is summarised in 7.7.

Municipality	$D_K = 0$	$D_K = 1$	$D_K = 2$	$D_K = 3$	$D_K = 4$	$D_K = 5$
Jojutla	3	5	3	26	17	1
Tlayacapan	3	7	7	11	4	1
Yautepec	5	15	9	10	2	1
Tepoztlán	5	15	12	3	1	1
Total	9.58%	25.15%	18.56%	29.94%	14.97%	2.40%

Table 7.7: Number of structures assessed by municipality and level of damage.

7.3 Results and discussion.

The results analysis for this experiment had three main stages. The first approach consisted of a direct comparison between the observed damages and the mean damage grade estimated using the seismic vulnerability index approach. A second stage of analysis considered some limitations found during the fieldwork campaign and, finally, a third stage considered the use of Machine Learning algorithms for assessing how suitable is its use for predicting the levels of damage and calibrating the weights of the Vulnerability Index Method for specific typologies and built environments.

7.3.1 Simple parameter-based analysis.

It is important to note that the qualitative scale for classifying the observed post-seismic damages on structures corresponds to intervals for mean damage grade μ_D . The first comparison for assessing the suitability of the method on the given number of building cases consisted in checking if the analytical value obtained for μ_D was comprised in the permissible range of the real/observed damage $D_{k,2017}$ (see Figure 7.7). A total of 104 out of the 166 cases (62.28%) present coincidence between the predicted μ_D and observed $D_{(k,2017)}$ levels of damage (see Table 7.8).

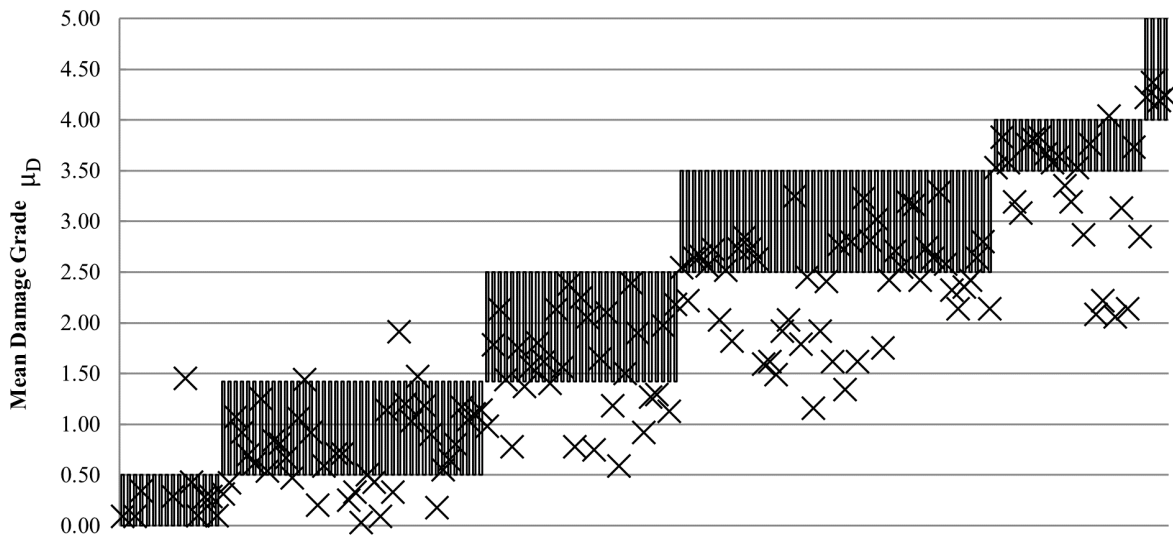


Figure 7.7: Comparison between the intervals for the permissible range of observed damage (bars) and analytical damage (black crosses) by sample.

When the method fails at predicting the level of damage, it is often an underestimation of it (i.e., analytical levels of damage were less severe than the real damages observed and described in situ). It should be noted that the semantic descriptors used in the VIM approach for modelling the built environments (type

of structures, materials, etc.) were enough for describing the buildings herein presenter. Nevertheless, it is pertinent to consider that some relevant phenomena or characteristics may not fit in this survey model.

Municipality	Successful	Failed	Success ratio (%)
Jojutla	27	28	49.09%
Tlayacapan	19	14	57.58%
Yautepec	30	12	71.43%
Tepoztlán	28	9	75.68%
Total	104	63	62.28%

Table 7.8: Summary of successful predictions for the level of physical damage.

For example, despite the general conservation status of the construction being a parameter assessed for determining the vulnerability to seismic actions, earth-based structures may have more specific deterioration issues and fragility due to moisture content in structural elements. This specific defect is not included in the original approach but can intuitively be significant for assessing the state of construction.

This observation becomes even more relevant when considering the number of constructions that had lost the external renders for aesthetic reasons. This discussion is not further developed in the context of this article since the moisture content of the constructions at the moment of the earthquake is unknown. Nevertheless, it provides an opportunity for discussing and adapting the VIM survey for future experiences.

Another reasonable explanation for this lack of representativeness is related to a condition that worsens the structural behaviour, such as an unfavourable soil-structure interaction. Besides, a certain grade of unrepresentativeness can be a consequence of the limitations for having reliable data acquisition, namely due to field restrictions (inaccessibility, lack of safe conditions for performing field works, etc.).

7.3.2 The role of uncertainty.

Given the access limitations during the fieldwork and the consequent uncertainties in the evaluation associated with certain parameters, it was decided to take into account the Quality Check (QC) approach proposed for the city of Atlixco [Ramírez Eudave and Ferreira, 2021d]. This approach adds a code for each parameter to express how reliable the data acquisition process (and, therefore, the grade assignment) was:

- QC0: High reliability. Grade verified with a high level of certainty. Data is explicitly contained on the datasheets and have been verified in situ.
- QC1: Medium reliability. Deduced from secondary sources, (photographs, drawings, etc).
- QC2: Low reliability. Reasonably based on typological similarities and extrapolation.
- QC3. Absence of information. The grade is merely indicative but still better than a random decision.

Parameters for which the reliability of the evaluation was considered to be QC0 or QC1 level, no further action is taken and the vulnerability classes assigned for that parameter are accepted. Otherwise, the hypothesis of having a lower vulnerability class than the initially proposed is sustained. Therefore, an alternative conservative assignation of the vulnerability class is adopted by downgrading one or two classes. respectively for QC2 and QC3 (e.g., from A to B or from A to C).

As an example, in a construction for which access was not granted, the surveyor may decide that the inner conservation status (assessed by parameter BP13) is good, according to typological similarities and previous experiences. But, since no visual confirmation was possible, a QC2 reliability level must be assigned to this parameter. This means that the vulnerability-oriented survey will initially consider BP13 with a grade A, whilst the conservative boundary of the vulnerability index will be calculated assuming that this same parameter can have a grade B (or C, in case of having a QC3).

Therefore, the mean damage grade μ_D becomes an interval with two boundaries: a lower limit that corresponds to the vulnerability class initially given during the field campaign and an upper limit that correspond to a more conservative assessment in which the uncertainties have been considered, as the safe side definition.

This approach is possibly easier to understand when expressed graphically, as shown in Figures 7.8 to 7.13. For each building, the boundaries for the analytical damage range, μ_D and $\mu_{(D,conservative)}$ (obtained by applying the VIM), are represented through a black horizontal bar and a cross, respectively, while the intervals for the discrete qualitative observed damage grades assigned (the real damages observed in the building) are represented through a white bar, facilitating the interpretation of the overlapping among both intervals.

With this approach, the vast majority of predicted damage intervals overlap with the corresponding intervals of observed damages (see Table 7.9). This observation is consistent with the results reported for Atlixco, supporting the feasibility of the joint use of an alternative and more conservative value for assigning an interval for the physical damage instead of closed and nominal values.

Municipality	Successful	Failed	Success ratio (%)
Jojutla	50	5	90.91%
Tepoztlán	34	3	91.89%
Tlayacapan	32	4	96.97%
Yautepec	40	2	95.24%
Total	156	1	93.41%

Table 7.9: Summary of samples in which the observed and estimated damages are overlapped.

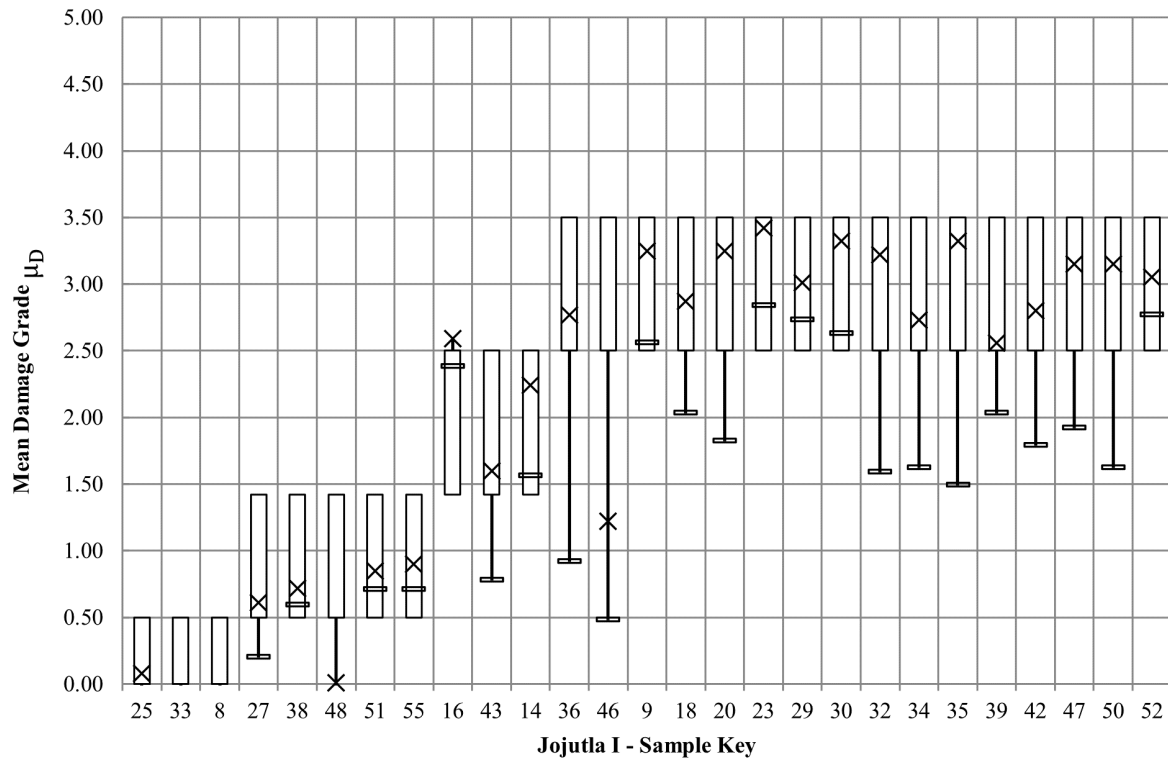


Figure 7.8: Analytical and real damage grade intervals for the municipality of Jojutla (1 of 2).

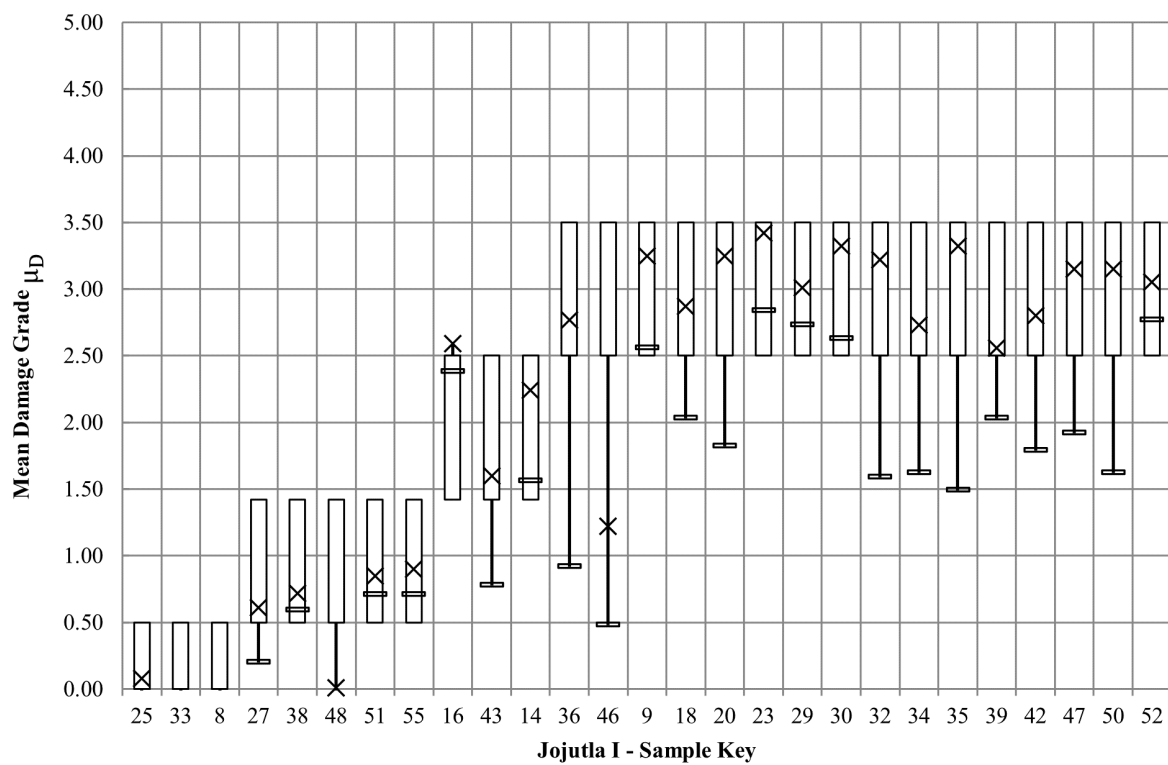


Figure 7.9: Analytical and real damage grade intervals for the municipality of Jojutla (1 of 2).

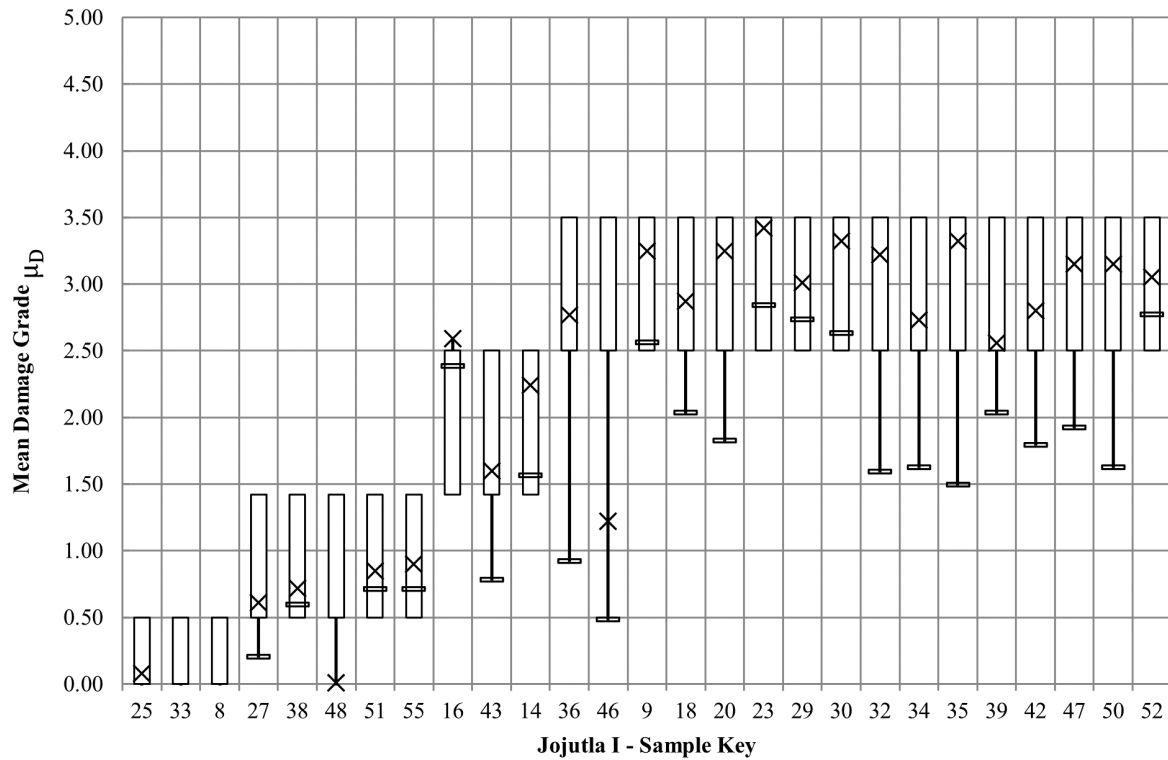


Figure 7.10: Analytical and real damage grade intervals for the municipality of Tlayacapan.

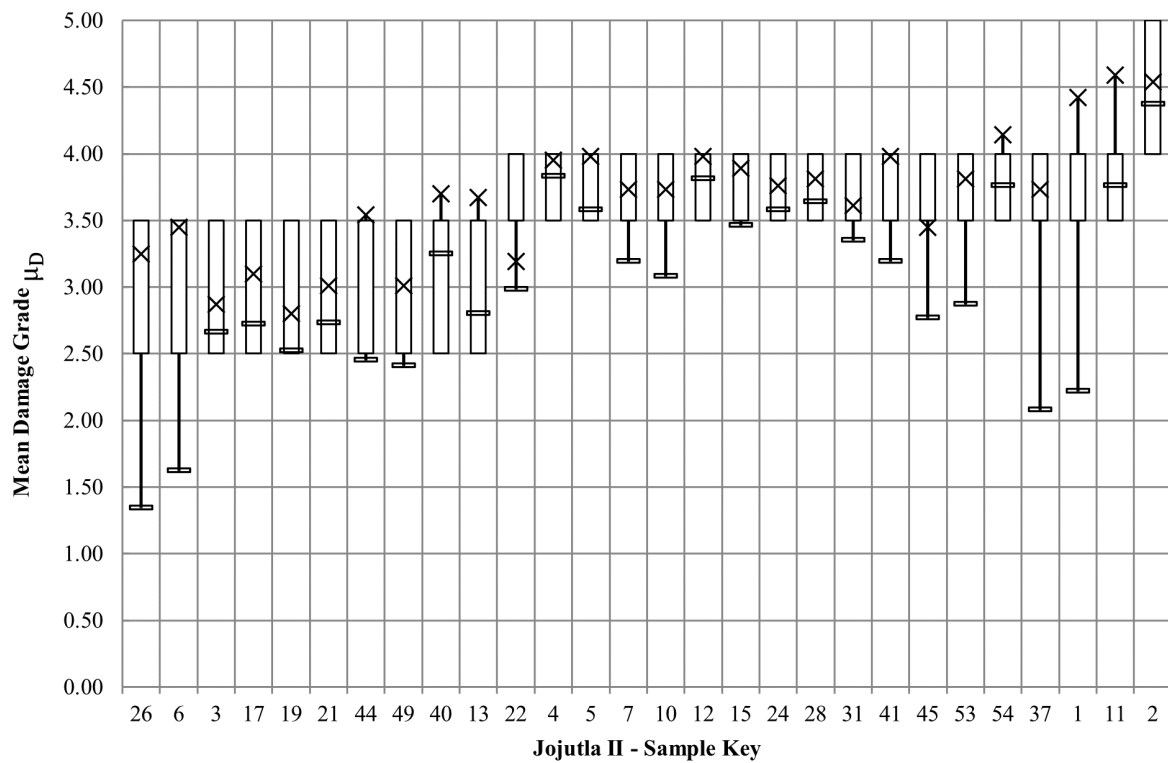


Figure 7.11: Analytical and real damage grade intervals for the municipality of Yautepec (1 of 2).

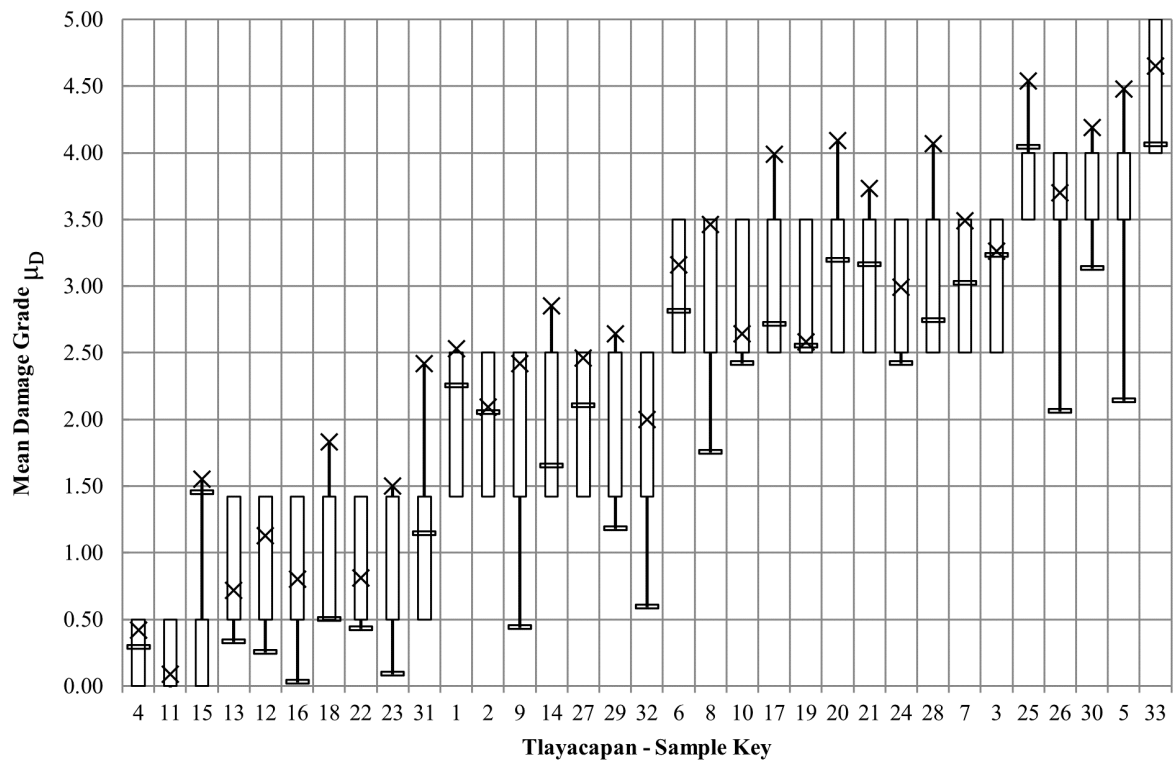


Figure 7.12: Analytical and real damage grade intervals for the municipality of Yautepec (2 of 2).

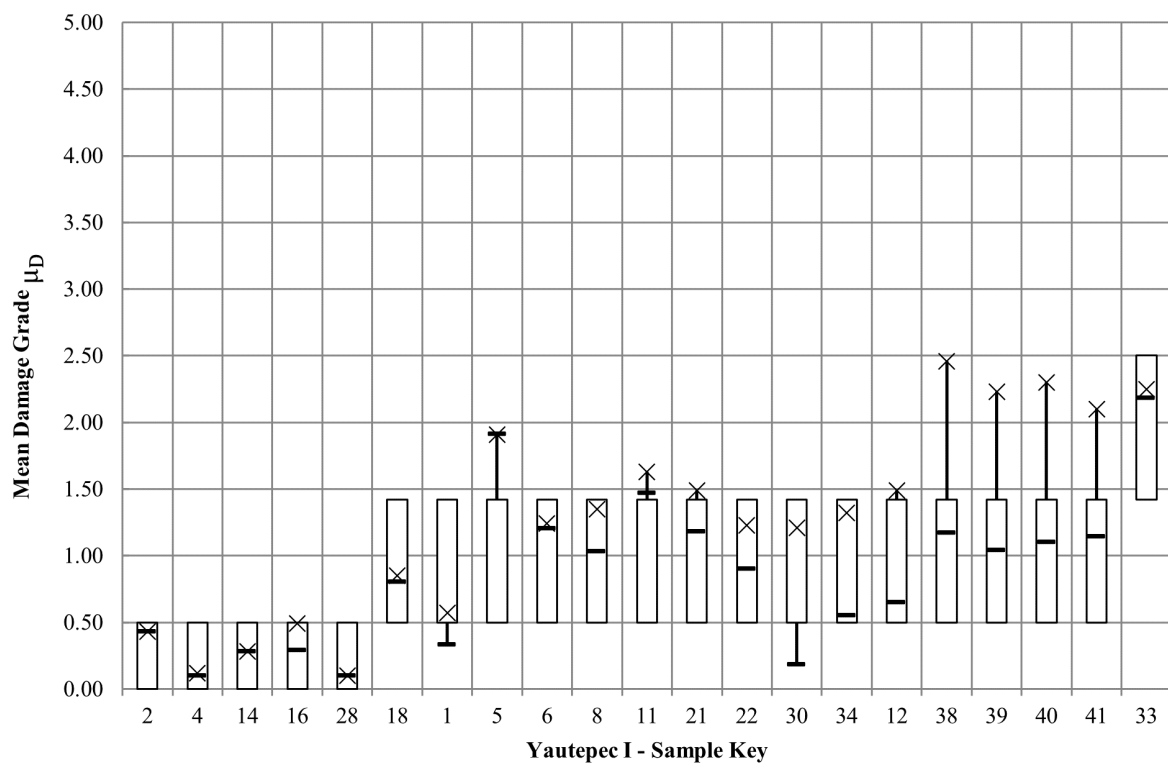


Figure 7.13: Analytical and real damage grade intervals for the municipality of Tepoztlán (1 of 2).

Nevertheless, this approach does not solve the potential lack of representativeness associated with the conceptual models used in the VIM approach. Even if the calibration and adjustment of the methodology by means of analytical approaches are possible, the experience herein presented explores the suitability of resourcing to machine learning tools for predicting the damage grades from the set of parameters already acquired, unveiling hidden patterns and potential redistributions of the weights originally proposed.

7.3.3 Machine Learning approach.

The use of trained algorithms for recognising patterns and subjacent relations has been demonstrated to be suitable for numerous problems in which the relations between input data and outcomes (results) still present hidden or not well-defined mechanisms. Given that the proposed procedure is intrinsically attached to a regressive analysis of cause-effect elements based on categories (both for the parameters and the damages), the use of computational analysis is a strong and suitable measure for expanding the boundaries of this methodology.

It is important to note that the VIM approach is based on an existing empirical parameter-based methodology built on the evidence of past events: the analysis from numerous seismic events, the classification of the structures and their damages, representing a process of domain knowledge Handcrafted Feature Extraction. This process is critical for recognising which descriptors (features) are more important for determining an outcome [Guyon and Elisseeff, 2006]. For the case of the seismic vulnerability of masonry structures, this feature extraction has been empirically conducted and refined based on numerous observations, leading to determining the set of 14 parameters used in this investigation. This approach is a response to the limitations that robust structural analysis (strongly customised in the case of historical structures) has when dealing with large numbers of buildings or constructions to be assessed.

Machine Learning principles.

Although the use of Machine Learning and Deep Learning approaches (subfields of Artificial Intelligence) for studying complex processes is not new, their use in the context of complex civil engineering applications is not generalised yet. A relatively recent field of application of Machine Learning algorithms is the health monitoring of historical structures and heritage buildings, in which heterogeneity, complexity and variability are still relevant challenges for more generalised approaches [Mishra, 2021].

The use of these resources should always be accompanied by awareness regarding their limitations, bias and the limits of the control that the user has towards the several “black boxes” that these processes imply [Vadyala et al., 2022]. It is possible to obtain apparent accurate predictions and structured models

even from weak evidence and scarce data. Therefore, to have a robust control of the representativeness of input data, the integrity of data and the correct selection of models and cases are critical aspects to consider. In this case, the existence of a precedent data model (that of VIM) is useful for contextualising the results obtained when performing the Machine Learning algorithm design and assessment.

Implementation.

The approach adopted for this case study accepts a series of assumptions related to the type and quality of data. The most important one is that the labelling of the input and outcome data has been directly adopted from the VIM methodology. In other words, the parameters, grading and levels of damage have been adopted as is, so the database used in the previous sections did not suffer alterations.

The general workflow herein presented is that proposed in the documentation of the freeware learning library scikit-learn [Pedregosa et al., 2012]. This library supports many of the most common classification, regression and clustering algorithms for Python programming environment, namely through the NumPy library. The implementation herein presented was programmed as part of the database front-end manager to work within the original database [Ramirez Eudave, 2022].

Importing data.

The vulnerability database was built in a GIS environment by using Geopackage files in native format. Thus, the management of the database was held by means of GeoPandas, a Python open-source library that supports the management of geospatial information as well as more typical non-geographical data frames. This library allows the management of GIS native files (Geopackages, shapefiles, etc) as tabular data keeping the integrity of georeferenced information. Therefore, these capabilities allowed us to read and import the database, namely the 14 parameters (and their associated vulnerability classes).

For this process, it becomes critical to assign labels and recognise which components of data represent features and target outcomes. In other words, it is necessary to identify which data is meaningful for conditioning the outcome. For example, the database includes the address of the constructions, an information that is not critical to explain the level of physical damage of the structure. Nevertheless, this dataset already contains fourteen labelled parameters (the labels are the parameters' classes) that we already consider valid for defining and estimating the level of damage (i.e., the outcome) of a structure in the context of a determined earthquake. The process of recognising these features is part of the so-called Handcrafted Feature Engineering, which can otherwise be performed by the means of domain knowledge or other approaches.

Given that this process is an inherent part of assuming the VIM methodology, all the fourteen parameters considered in the database are meaningful for defining the level of physical damage (outcome) of the structure. Nevertheless, in contrast to the VIM approach, the ML algorithm does not assess the parameters from a given weighted importance (i.e., the only information the algorithm has is that the parameters are related to the outcome). Instead, the ML algorithm will fit a distribution of weights per parameter that represent a more representative model. This clarification is especially relevant because some other ML processes are also aimed at the identification of learned features from raw data [Khurana et al., 2018].

Cleaning and splitting data.

This step was performed in the scope of input data presented in sections 3.1 and 3.2, in which the integrity of the database and the completeness of entries were verified. According to the good practices reported in similar classification problems, 20% of data was reserved for performing verification tests. This fraction may vary according to several criteria and the size of the sample, but common practices in this field often accept an interval of 15-20% as a reasonable ratio.

Creating a model (algorithm selection).

The selection of a suitable algorithm is one of the most critical steps for representing a problem with Machine Learning tools. For this exercise, a Supervised Learning approach (i.e., data for training associates sets of features with specific outcomes that are expected to further predict new sets of features) was carried out. Given that the target outcome consists of discrete damage grades (a level of damage $D_K = 0, 1, 2, 3, 4, 5$), the model has been categorised as a classification problem (i.e., data is labelled with two or more classes and the Machine Learning processes would find valuable vectors for pointing outcomes from the labelled features). As schematised in Figure 7.14, the field dataset (the 166 observations that include the parameter's grading and the real post-seismic levels of damage) is used for training the RFC algorithm, so the algorithm recognises patterns between the parameters and the levels of damage.

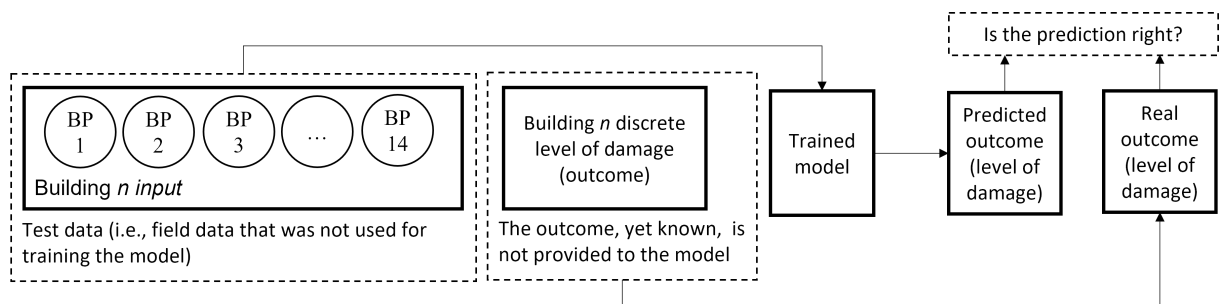


Figure 7.14: Flow diagram of the training and prediction processes.

This trained model replicates these patterns for predicting the outcomes that can result from a given combination of parameter grades. The prediction can be used for obtaining outcomes from new samples and/or assessing the accuracy of the model by predicting already-known outcomes. In this case, 20% of the data was reserved for performing this assessment process.

The problem herein presented is a classification and regression task since the parameters are given but their relative impact on the outcome is not provided to the algorithm. If some parameters (features) of the income data are not useful, this algorithm minimized/reduces its relative sensitivity on the model.

By following the observations of Buitinck et al. [2013], this problem can be modelled by the means of the Random Forest Classifier (RFC) learning algorithm. This algorithm ensemble numerous decision trees (i.e., flowchart models in which an outcome is a product of a specific path of several conditional statements or nodes) that fit fractions of data instead of creating a unique tree model. This algorithm prevents model overfitting by using multiple trees and the so-called bagging method.

As schematised in Figure 7.15, the bagging process consists in randomly splitting the complete dataset into a series of equally sized datasets. Since the selection is randomised, each observation can appear in more than one tree. The number of trees is not limited by the number of observations of the dataset. Each subset is used for training a customised individual decision tree (i.e., for fitting a partial model based on the subset of observations). When a new observation is introduced to the model, each tree “votes” according to its particular training. The complete model assigns an outcome based on the overall “votes” of the partial decision trees. The sum of all these random trees represents the so-called “Random Forest”.

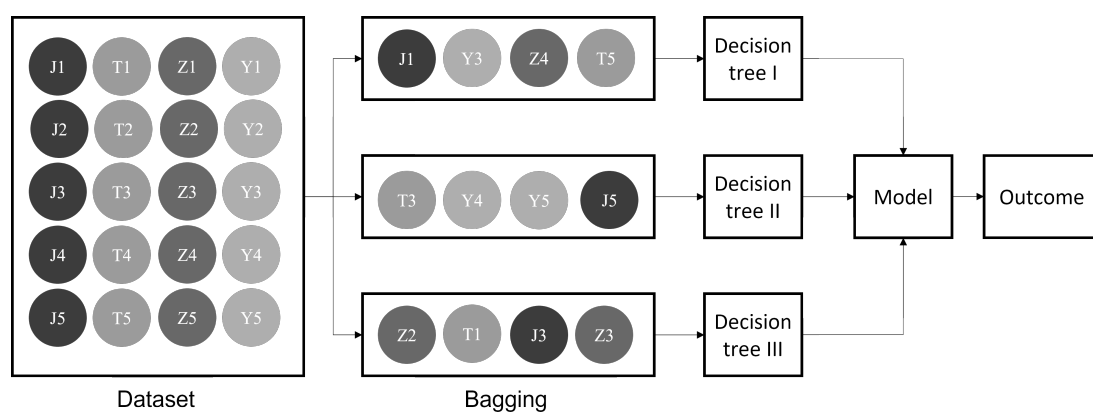


Figure 7.15: Schematisation of the bagging process.

Among the many available algorithms for performing classification works, the RFC was considered especially suitable because does not make assumptions about the underlying distribution of data and because it permits a better understanding of the relative influence that the features have (assuming that all the selected features are meaningful).

Given that this classification problem departs from an already-established survey (that has been tested, calibrated and enriched based on the evidence of multiple seismic events) instead of raw data, we accept that all the features are valid and influence the outcome. There is a subjacent decision-tree structure for the VIM analytical procedure. The conceptual compatibility between the analytical development of the VIM approach and the RFC is therefore considered key for comparing both techniques.

The application of RFC for modelling seismic vulnerability-related phenomena has some relevant precedents, such as the mapping based on damages after seismic events [Han et al., 2020], post-earthquake reconnaissance for reinforced concrete structures [Midwinter et al., 2022] and structural elements damage models [Lei et al., 2020].

Training the model, making predictions and evaluating the model.

The model herein presented was trained by using the hyperparameters (parameters whose values control the learning process and determine the values of model parameters that a learning algorithm ends up learning) setup summarised in Table 7.10. No relevant characteristics of the dataset seemed to be critical for rejecting the default settings, except the number of trees, which was set according to the observations of Oshiro et al. [2012]. Given the nature of this classification problem (a relatively simple one), no further adjustments were needed.

Hyperparameter	Description	Value
max_depth	Longest path between root node and leaf node	"None" (unlimited)
min_sample_split	Minimum number of observations in any node to split it.	Default (2)
max_leaf_nodes	Limits the growth of the tree.	"None" (unlimited)
min_samples_leaf	Minimum of samples present after splitting a node.	Default (1)
n_estimators	Number of trees in the forest.	128
max_features	Maximum number of features provided to each tree	"Auto"
bootstraps	Data point sampling method. When set as "true", there is replacement.	True
criterion	Method used for measuring the quality of a split.	Gini

Table 7.10: Hyperparameter setup for training the RFC algorithm.

A series of predicted classifications were obtained by using the data reserved for testing the model (34 random samples), integrating a new data frame that allowed the comparison between the real outcomes (the $D_{K,2017}$ levels of damage) against those predicted by the model (Figure 7.16).

This process allowed us to understand how representative and effective the model is. The metrics for evaluating the model were obtained by using the classification report embedded in the Sklearn package (see Table 7.11). This report offers three main metrics for each class:

- Precision. The ratio of successful identifications of a class divided by the number of times that the label was predicted in the model. This is the ratio of the true positives divided by the sum of true and false positives.
- Recall. The ratio of successful identifications of a class divided by the number of samples that belong to that class. This ratio expresses how many relevant identifications were retrieved.
- F1-score. Represent the harmonic mean between precision and recall, representing the performance of the model.

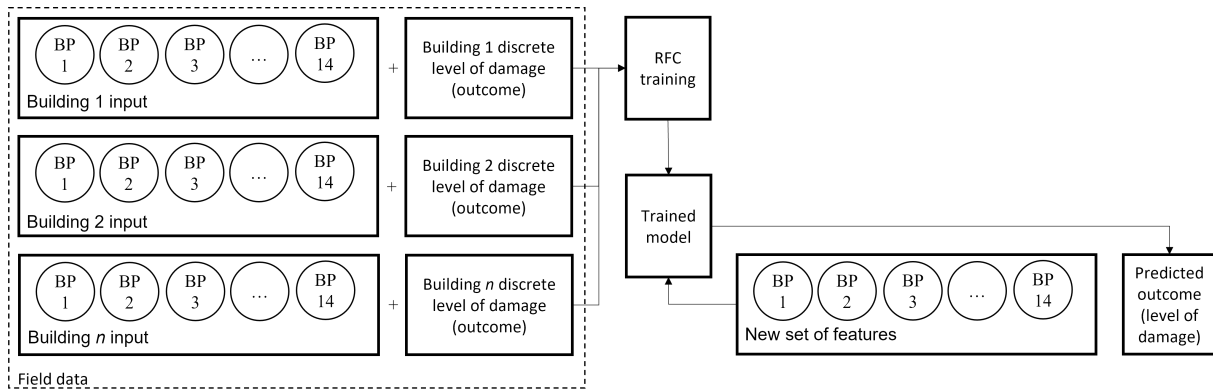


Figure 7.16: Schematisation of the evaluation of the model.

Class D_k	Precision	Recall	F1 Score	Samples
0	1	1	1	3
1	1	1	1	8
2	1	1	1	4
3	0.92	1	0.96	12
4	0.83	0.83	0.83	6
5	0	0	0	1
Macro average	0.79	0.81	0.80	34
Weighted average	0.91	0.94	0.93	34

Table 7.11: Classification report.

An explicit representation of the results is the confusion matrix (see Figure 7.17), in which the correspondence between the true and predicted labels (i.e., discrete levels of damage) is shown. This confusion matrix exhibits how most of the classes were correctly identified by the model, but there is a lack of representativeness in identifying the highest level of damage $D_K = 5$. This phenomenon can be easily associated with the relatively small number of samples used for training purposes in this class (4 out of 167, 2.4%, however it appears only once in the test split of the sample) since this is the most infrequent class, it is expected to be less likely recognised by the algorithm.

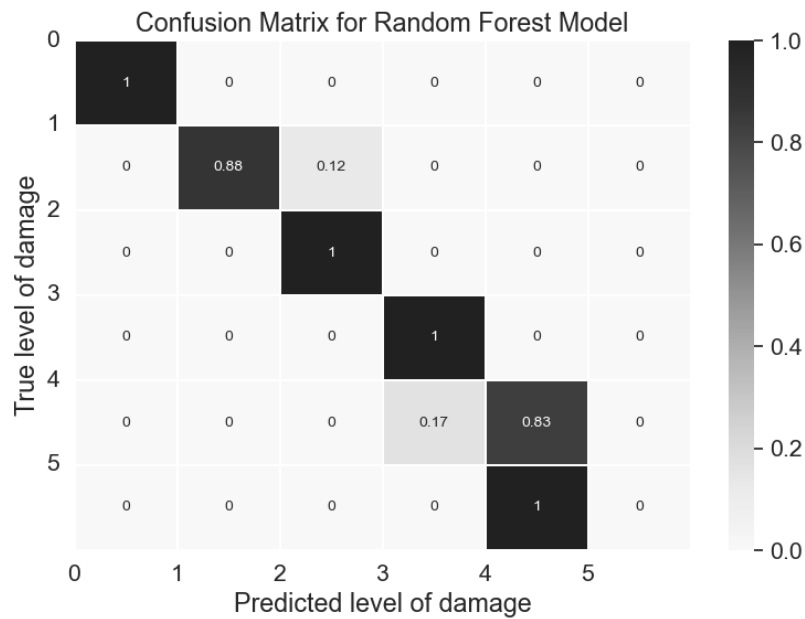


Figure 7.17: Confusion matrix. True values correspond to observed levels of damage.

It is possible to retrieve which is the relative impact that every parameter has in the classification process. At this point, it becomes convenient to be aware of the limits imposed due to the variability throughout the sample, i.e., the impact of a determined parameter will be smaller if it does not present relevant variations for differencing samples. The sample herein studied presented relatively small variations in some parameters given the typological coherence amongst the structures (Figure 7.18). The feature importance (see Figure 7.19) of the model reflects this phenomenon.

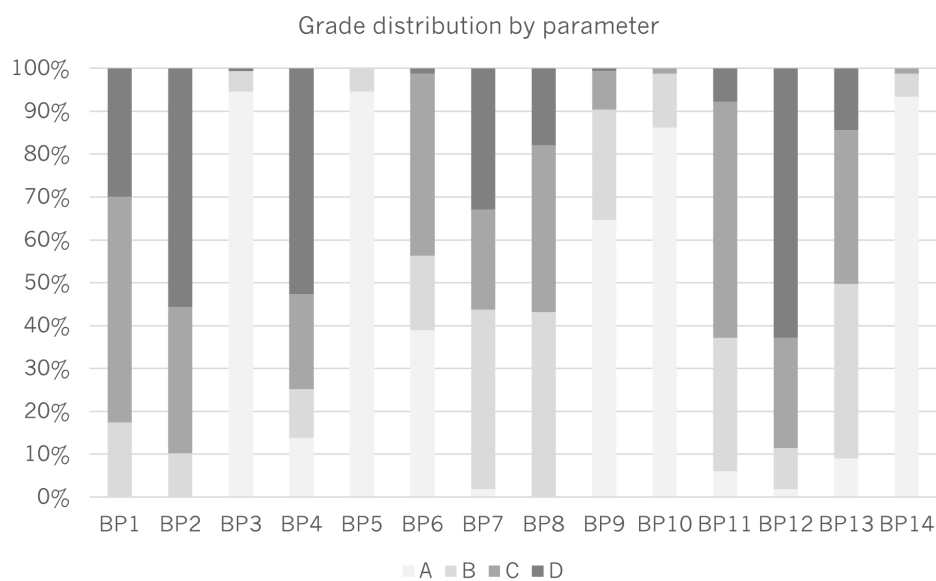


Figure 7.18: Vulnerability class distribution per parameter.

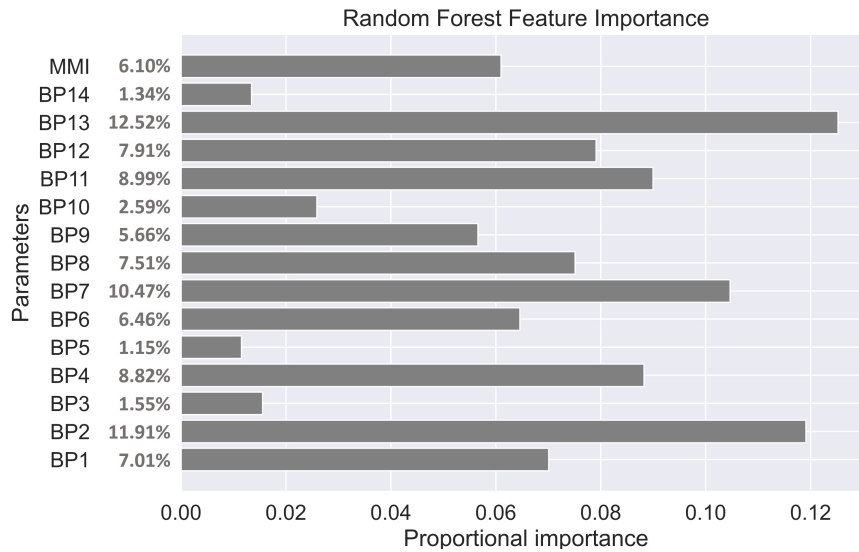


Figure 7.19: Relative importance by feature according to the RFC model.

The model for this sample exhibits relatively low importance for certain parameters, such as BP3 (Conventional strength), BP5 (Number of floors) and BP14 (Non-structural elements), which is consistent with the typology observed in situ: one-storey constructions with no remarkable features in the facades and with similar plan distributions. On the other hand, parameters such as BP2 (Quality of the resisting system), BP7 (Aggregate position) and BP13 (Conservation state) are critical for assigning a vulnerability class. Regardless of the physical meaning of these parameters, the algorithm identifies that BP2, BP7 and BP13 seem to have a more consistent effect in the outcomes, and it determines that these parameters are strongly conditioning the results. It is convenient to recall that, therefore, this weight distribution can be seriously limited when analysing a very different typology that would become an “outlier”, such as a building with more than three storeys.

The most obvious way for improving this approach is to enlarge the dataset to enhance the representativeness of extreme values. The generation of synthetic data under the assumption of normality was considered. To check the suitability of this approach (e.g., by using Montecarlo or Latin Hypercube sampling methods), the normality of the distribution of the observed level of damage was assessed by the means of the Kolmogorov-Smirnov test. The normality hypothesis H_0 is not supported at a significance level $\alpha = 0.05$, obtaining P-values < 0.00001 and, therefore, this experiment is not suitable based on the existing evidence and the dataset was not enlarged. This procedure would have been useful for enlarging the dataset without losing its representativeness and having a larger number of extreme observations. It is important to keep in mind that larger datasets obtained in situ may provide evidence for finding representative statistical distributions for the levels of damage.

7.4 Final remarks.

This work presents a series of processes based on the vulnerability assessment of structures damaged as a consequence of the 2017 earthquakes in the centre of Mexico. A total of 167 constructions were surveyed to obtain a set of fourteen parameters that allowed the estimation of vulnerability index and consequently the determination of mean damage grade when subjected to a determined intensity earthquake.

The sample herein presented corresponds to a typologically homogeneous housing dataset distributed throughout four municipalities of the State of Morelos, emphasising the predominance of adobe-based structures. All the constructions were surveyed in situ, accomplishing a database containing the pre-seismic characteristics of the buildings. This process was possible with the support of the National Catalogue of Historical Monuments, interviews with the building owners and users and visual in-situ inspections. The level of physical damage that every construction evidenced/experienced was compared with the predicted level of damage according to the VIM methodology.

A first attempt consisted of the direct application of the method, neglecting some sources of uncertainty identified during the surveying campaign (incompleteness of information, the impossibility of accessing all constructions, etc), resulting in a 62.28% of acceptable agreement (i.e., the estimated damage was comprised with an interval of the real/observed damage).

A second exercise was developed by enriching the method with the addition of a quality check in which the uncertainty for assigning a certain vulnerability class is accepted and integrated for obtaining an alternative, more conservative, level of physical damage. This process led to having two values (that of the first attempt and a conservative one) for constituting a range for the mean damage grade. This approach was revealed to have a better fitting with the field observations since 93.41% of the predicted and real/observed defined intervals are overlapped.

A third approach was performed by the means of Machine Learning techniques, specifically by using a Random Forest Classification algorithm. This algorithm was trained for solving the categorisation of the level of damage by establishing other relations among the parameters rather than the one used for the analytical approach. Despite the overall performance of the model, it is considered satisfactory (with an accuracy score of 94.12%), since these results are limited to the size and typology of the sample.

The analysis of the proportional importance of the parameters demonstrates that the trained model would not be suitable for assessing constructions with a very different typology. Furthermore, the number of samples, specifically in what concerns the relatively small number of samples for the extremes of the levels of damage (no damage at all or total collapse, corresponding to $D_k=0$ and $D_k=5$ respectively) difficult

to have a good representation of these constructions. Since the normal gaussian distribution of damage throughout the sample cannot be statistically sustained, some approaches for generating synthetic data are not suitable. Therefore, the size of the sample is considered a limitation for obtaining more conclusions than the ones presented in this work. A necessary further development in this sense is the creation of larger datasets (based on precedent seismic events) that can be used for finding typical statistical distributions as well.

The assumption of using this algorithm as a suitable tool for similar problems is sustained given the positive results of classifying the buildings into five damage classes. The evidence of typological fitting of the model is consistent with some empirical observations on site and offers an interesting field for enhancing the capabilities of the VIM approach by adjusting the relative weight of the parameters for diverse typologies in which there is enough data for training the model. In other words, it is possible to take advantage of the vulnerability survey as a Handcrafted Feature Extraction base for developing straightforward models under the basis of regional and/or typological sets.

The implementation process presented and discussed in this article prove that the weights originally assigned to the VIM parameters can be adjusted to obtain a better fit (for better representing) to the common vernacular typology found in Morelos. Based on this observation, it is thus possible to affirm that this same process can be applied to develop customised models for locally built environments. The existence of information regarding previous seismic events (characterisation of the constructions, levels of damage, etc) can be used to train this ML algorithm and predict the effects that future seismic events may have on specific buildings typologies.

The tools developed for this experimental program (namely those related to data acquisition and management) make possible the systematisation and analysis of existing and new data within the workflow herein presented.

Chapter 8

Concluding remarks and future research directions.

Urban-scale vulnerability assessments play a key role in risk assessment and mitigation of seismic events. These assessments depend primarily on an adequate design of the descriptive models, the implementation of suitable approaches for data acquisition, feasible data management and storage frameworks, and the possibility of providing feedback and calibration to the entire system when new data is available. A feasible integration for this purpose lies on the use of Geographical Information System databases for storing and managing straightforward databases. Among others, this implementation offers the capability of being integrated together with external systems and services for having urban-scale, decentralised, redundant and real-time updatable databases.

It is possible to design an integrated and holistic data framework for characterising the historic urban landscape by using the Aristotelian theory of the causes. The demonstration herein presented opens the possibility of integrating the vulnerability-oriented semantic model together with complementary models that represent other important layers of data. For example, the social and economic vulnerability can be framed in this data framework for carrying-out complementary assessments. Furthermore, this data structure has been successfully implemented in the GIS environment, sustaining the previous assumption of integrating platforms such as BIM and HBIM. The approach herein presented for structuring the semantic model permits to explore different scales, virtually covering both, urban and building scales.

The comparison between the National Catalogue of Historical Monuments and the proposed parametric methodology demonstrated a relevant compatibility at the level of semantic models of constructions, facilitating the implementation of seismic vulnerability assessments. The first experience permitted to validate the representativeness of the analytical levels of damage against the real effects that the 2017 earthquakes had in a set of constructions of the city of Atlixco (Puebla). Nevertheless, some limitations were found, particularly when aiming at the design of methods for considering the inherent epistemic uncertainties.

The method (together with the uncertainty control approach) was successfully implemented in a GIS

database, whose capabilities were extended by the means of two external tools. Firstly, a straightforward Python-based environment was developed for performing changes and editions in the database while keeping the integrity of the GIS layers. This tool demonstrated to be robust and stable enough for managing urban-scale databases in the states of Puebla and Morelos. The second explored capability was to publish the database as GIS layers by using the WFS-T protocol, facilitating its online management by using open-source software and browser consulting.

The experience performed in Atlixco (Puebla) demonstrated the suitability of using the methodology herein proposed by adding an uncertainty control. This experience exhibited a good fitting between the analytically obtained damages and the post-seismic scenarios of 2017. This first large-scale experiment put the bases for future analyses, namely related to implementing a weight recalculation based on typological features, sustaining the possibility of extending this analysis to other historical environments.

A more extensive application of this approach in several municipalities of the state of Morelos overcame many of the limitations found during the first experiences, namely those related to the number of assessed constructions. The data acquisition of 167 constructions in four settlements was the opportunity for testing the robustness and suitability of the tools developed in GIS environments: a database, cloud-based storage and distribution, and a customised Python-based interface for management. Furthermore, the development of this interface was the base for a data treatment framework in which an innovative Machine Learning approach was implemented. The use of trained algorithms for finding patterns between the Vulnerability Index Method survey and the real-life outcomes (i.e., the levels of damage of the structures) for a specific construction typology demonstrates the suitability and applicability of classification-based algorithms (such as Random Tree Classification) for performing relatively simple calibrations of the method based on local and/or specific construction traditions. This finding can be the base for larger and extensive explorations in which already existing information (related to damages in past seismic events) can be used for performing regressive calibrations. Therefore, the same set of parameters can be applied to different environments and typologies by only adjusting the relative weights, obtaining more reliable and representative assessments.

Under the light of the findings herein presented, there is a series of works that are open for further development:

- Implementation of a script or program for querying the features (parameters) of the Vulnerability Index Method directly from existing BIM or HBIM models, by using the IFC protocol.
- The use of the mechanical properties experimentally obtained for performing a sensitivity analysis in order to assess the representativeness of the assumed model.

- The replication of the assessment method in a different construction environment (e.g., given a specific type of masonry works) in order to test the calibration proposed by the means of Artificial Intelligence.
- To perform urban-scale risk analysis under the basis of the building-scale vulnerability assessment. This risk analysis would include the study of the serviceability limits of the structures (as a function of the seismic intensity) for supporting basic services and the potential disruption in the urban functions due to damages and collapses. Furthermore, this analysis would facilitate the obtention of post-event scenarios for designing emergency response strategies.
- Assess the impact that retrofitting and strengthening actions can have for reconfiguring the post-event scenarios, reaching the configuration of cost/benefit analyses according to a series of potential solutions based on the weaknesses identified by applying the Vulnerability Index Method survey.

All the experiences herein reported suggest that the vulnerability assessment of historical masonry constructions is possible even with a limited set of resources. Furthermore, this conclusion implies that the vulnerability status of many of the constructions damaged during the 2017 earthquakes was able to be opportunely and straightforwardly characterised. In other words, many of the damages and losses would have been anticipated by implementing a relatively simple but proactive assessment of the historical building stock. Even if this assumption is easy to be retroactively stated, it is a necessary conclusion that should be present for making ethical decisions while performing any research work. Scientific research is one of the several actions for assembling safer and more resilient communities.

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Appendix A

Description of the façade parameters used in Chapter 4.

Tables A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, A.9, A.10, A.11, A.12 and A.13 refer the grading criteria for the parameters of the façade-based vulnerability index method.

A	B	C	D
$H/B < 0.40$	$0.40 \leq H/B \leq 0.60$	$0.60 \leq H/B \leq 1.00$	$H/B \geq 1.00$

Table A.1: FP1. Geometry of façade. Based on the length (B) and height (H) ratio.

A	B	C	D
$H/s \leq 9$	$9 < H/s \leq 15$	$15 < H/s \leq 20$	$H/s > 20$

Table A.2: FP2. Maximum slenderness based on the height (H) and thickness (s) of the wall.

A	B	C	D
Below 20 %	Below 35 %	Below 60 %	Above 60 %

Table A.3: FP3. Area of openings. Ratio between the area of openings with respect to the entire façade.

A	B	C	D
Regular size and height-aligned openings	Openings of regular or irregular dimension misaligned horizontally in more than 1/2 of its height	Openings of regular or irregular dimension misaligned vertically in more than 1/2 of its height	Openings of regular or irregular dimension fully misaligned horizontally or vertically and/or large openings at floor level

Table A.4: FP4. Misalignment of openings. Vertical and horizontal alignments of the openings.

A	B	C	D
In between two adjacent façades of the same height.	One façade of the same height and a shorter one	Between two smaller adjacent façades	Only adjacent to a shorter façade

Table A.5: FP5. Interaction between façades. To take into account «pounding effects» that may occur due to adjacent façades with different heights.

A	B	C	D
Good quality brick masonry (solid or up to 45 % voids). Well carved stone, well mortared and fastened/clamped with transversal connection between the layers of the wall.	Brick masonry (perforated in more than 45 %). Well carved stone masonry with little homogeneous units throughout the wall. Irregular stone masonry with transverse connection between the layers of the wall.	Low-quality brick masonry with laying and connection irregularities. Stonemasonry with unworked units of heterogeneous dimensions. Irregular stone masonry without cross-connection, but well mortared and locked.	Poor quality brick masonry with inlay of stone fragments. Stonemasonry with uneven units and no careful locking (and with voids). Irregular stone masonry without cross-connection, poorly mortared and fastened.

Table A.6: FP6. Quality of materials. It evaluates the type of masonry.

A	B	C	D
Absence of cracks.	Cracks in the coatings and points of stress concentration, such as corners. Signs of reparation of cracks	Signs of settlement, cracks in the middle of openings (bending), shut-out cracks with increased opening in height, cracking of cover, oblique cracks.	Penetrating cracks and severe disintegration signs. Façade with out-of-plane deformation.

Table A.7: FP7. State of conservation.

A	B	C	D
$0 \leq P < 25 \%$	$25 \leq P < 50 \%$	$50 \leq P < 75 \%$	$P > 75 \%$

Table A.8: FP8. Replacement of the original floor system. Percentage P of the original horizontal diaphragms that were replaced by heavy concrete-based structures.

A	B	C	D
The façade is well-connected to the orthogonal walls through metallic strapping elements and tie rods. Masonry walls with good arrangement and locking.	The façade is well connected to the orthogonal walls by good techniques of laying and locking the masonry in the wedges and with are no signs of embrittlement. The conditions for class A are verified only in some wedges and orthogonal connections.	The façade is not well connected to orthogonal walls (a common situation for band buildings constructed in distinct phases), but there are no signs of embrittlement. Class B conditions may only be checked on some wedges and orthogonal links.	The façade shows deformations, with considerable risk of collapse (fissures that enounce this situation of lack of stability). There is detachment, disconnection and/or cracking through the wedge zone and orthogonal connections.

Table A.9: FP9. Connection to orthogonal walls.

A	B	C	D
$e > 75 \%$	$50 \% < e < 75 \%$	$25 \% < e < 50 \%$	$e < 25 \%$
If the supporting zones of the floors (FSZ) are fragilized, i.e., if they show signs of deformation, rotting, retraction, severe distortion (DR) or lack of circulation safety (LS), the grading must be as follows:			
B	C	D	-

Table A.10: FP10. Connection to horizontal diaphragms. Evaluates the efficiency of the interaction between the façade and the diaphragms, regarding the percentage e of diaphragms with an efficient connection.

Lateral thrust action.		Class	Conservation status	
			Bad	Very bad
No thrust (e.g., truss system with any horizontal element that cancels horizontal thrust).	Strapping reinforce perimeter OR tie rods	A	B	C
No thrust (e.g., truss system with any horizontal element that cancels horizontal thrust).	No strapping reinforce perimeter NOR tie rods	B	C	D
Little thrust (e.g., slightly asymmetric systems, sloped roofs with no horizontal element, and simply sloped floors with a span/height proportion $l/h < 20$).	Strapping reinforce perimeter OR tie rods	B	C	D
Little thrust (e.g., slightly asymmetric systems, sloped roofs with no horizontal element, and simply sloped floors with a span/height proportion $l/h < 20$).	No strapping reinforce perimeter NOR tie rods	C	D	D
Thrust (e.g., simply sloped roofs with no truss with a span/heigh proportion $l/h > 20$).	Strapping reinforce perimeter OR tie rods	C	D	D
Thrust (e.g., simply sloped roofs with no truss with a span/heigh proportion $l/h > 20$).	No strapping reinforce perimeter NOR tie rods	D	-	-

Table A.11: FP11. Impulsive nature of the roofing system. Equivalent to the [P12] parameter of the Vulnerability Index Methodology, «Roofing system».

A	B	C	D
No balconies, plaques, ornaments, flower boxes, mechanical equipment, etc.	Only light elements attached like lights, signs, awnings.	Medium weight elements, such as equipment, air-conditioned, etc.	Balconies, parapets or other heavy elements attached to the façade.

Table A.12: FP12. Elements connected to the façade.

A	B	C	D
Np improving elements	Exterior stairs, arches, giants, etc.	Presence of reinforced plasters (e.g., with synthetic meshes)	Strengthening actions.

Table A.13: FP13 Improving elements. Elements that might help the structural performance of façades, mitigating out-of-plane mechanisms.

Appendix B

Description of parameters used in Chapters 5 and 7.

Type and organisation of the resisting system (BP1): This parameter assesses the type of resistant system based on the organisation of the walls, the quality of the construction fabric, the efficiency of the connections of the orthogonal walls and the eventual use of building codes for seismic design or retrofitting. The classes depend on the accomplishment of a series of properties of the walls, as summarised in Table B.1. The existence of perimetral beams or straps and tie-rods is uncommon in Mexican typologies. Hence, the proposed classes for Atlixco building stock depends on the existence of an adequate project and on the quality of the bonding, interlock, and structural connections. For Atlixco, this information may be taken from the information available in fields F4, F8, F13, F14, F15, F16 and F17 of the data sheet.

Class	Original definition (Vicente [2008])	Adjustments for Atlixco, Puebla
A	Built according to earthquake design codes or guidelines or, alternatively, strengthened according to codes for retrofitting and reparation that guarantee efficient connections amongst vertical elements and amongst vertical and horizontal elements.	Repaired, reinforced and/or built according to the construction codes. The project and execution had the corresponding licenses and have been approved by the INAH or other corresponding authority.
B	There is good bond and connections of orthogonal masonry walls. There is an efficient transmission of vertical and shear loads. There are perimetral beams/straps and tie-rods in all floors, with an adequate cross section and anchorage according to the thickness of the wall.	There is no evidence of the criteria of (class A), but the visual information allowed to conclude an adequate bonding and interlocking of the walls. The elements assure an efficient connection and transmission of vertical and shear loads.
C	The building does not present the connections stated for class B or present them in some floors. Nevertheless, there is a good connection among orthogonal walls due to an adequate bond and locking of masonry.	Conditions of class B are not present in at least one visible structural connection.
D	The building does not present well-connected walls. Total absence of tie-rods and straps.	Conditions of class B are not present in any visible structural connection.

Table B.1: Classes for the parameter BP1.

Quality of the resisting system (BP2): This parameter assesses the quality of masonry based on three aspects, see Table B.2:

a) Homogeneity, shape, size, and material of the masonry units, as well as the joint mortar composition.

b) Configuration and bonding of the masonry fabric. It becomes relevant to recognise if there are well-defined and apparent vertical and horizontal joints or if there is an irregular stone laying that leads to an irregular mortar joint distribution. The presence of brick or stone courses, constituted by units with the total width of the wall) or the existence of relatively large units of stone next to wall openings or corner angles does not denote a lack of homogeneity.

c) Presence of transversal connection elements with the width of the wall, in cases of two leaves wall (common in the case of stone masonry).

The Mexican catalogue is much less explicit when describing the material nature or source of the walls, giving some short material descriptions that do not provide information about the bonding or joints (Field F4). Furthermore, there is a relevant semantical divergence since the materials are not selected from a closed set but are declared as a text chain in which every cataloguer is able to introduce very specific terms. The criteria for Atlixco derived from the association of the descriptions found in the Catalogue and those taken from Vicente Vicente [2008]. The semantic descriptions found in the Catalogue are often over-generalising and may fail at representing the real materiality of the construction. Moreover, the class definition of this parameter is supported, in many cases, with pictures instead of the given description, allowing to classify accordingly.

Class	Original description (Vicente [2008])	Adjustments for Atlixco, Puebla
A	(A1) Stone masonry with homogeneous units in size and material, well carved or cut (parallelepipeds), good bonding and good quality mortar, with vertical and horizontal joints; (A2) Low porosity stone masonry with good bonding and interlocking and good vertical and horizontal joints. Good quality mortar. (A3) Masonry with perforated units (<45% of voids) with good vertical and horizontal joints and good quality mortar. (A4) Stone masonry with structure of timber (gaiola pombalina), with a good state of conservation, efficient connections between the elements of timber and no signs of decay by biologic attack or moisture decay. (A5) Solid brick masonry or solid blocks with good layering and interlocking; vertical and horizontal joints with good quality mortar. (A6) Strengthened and consolidated masonry (crack injections).	Brick or stone masonry.
B	(B1) Stone masonry with units of heterogeneous size, but well carved or cut and well bonded along the length and width of the wall. Good quality mortar. (B2) Stone masonry with uncarved or barely carved units. Transversal connection: stones or ceramic pieces across the width of the wall. Good quality mortar. (B3) Adobe masonry laid at one time, or one and a half times, with mortar of good quality. (B4) As A3, but only present horizontal joints or medium quality mortar. (B5) As A2, but with medium quality mortar. (B6) As A5, with signs of decay in timber or discontinuity of the elements.	Brick or stone masonry and adobe.
C	(C1) Coarsely carved stone masonry, irregular in shape, with irregular locking and laying. Medium quality mortar. (C2) Stone masonry with rounded and irregular units. Transversal connection and medium quality mortar. (C3) Solid brick masonry with deficient laying and poor mortar quality. (C4) Stone masonry with irregular units. Irregular laying and low-quality mortar. (C5) Two leaves stone masonry with irregular units, heterogeneous stone fragments and a solid quality core (consolidated filling material). Irregular laying and medium quality mortar. (C6) Adobe masonry overlayed at one half of length. Medium quality mortar.	- Adobe, rounded stone, and clay brick. - Stone masonry and brick masonry. - Rounded stone, volcanic stone, and clay brick. - Adobe, round stone, and clay brick.
D	(D1) Rammed earth (D2) Unworked stone masonry, with medium or high porosity. Deficient unit laying (with voids), without transversal connections. Low quality mortar. (D3) Brick masonry with units of low quality and laying with the use of unit fragments. Deficient layering and interlocking. Low quality mortar. (D4) Two leaves stone masonry with a partially empty and unstable inner core. Low quality mortar.	Adobe

Table B.2: Classes for the parameter BP2.

Conventional strength (BP3). This parameter assesses the global shear strength of the building when subjected to seismic action (equivalent force approach). The base assumptions are an infinite stiffness of the diaphragms (neglecting irregularities in plan), and the strength is independently calculated in two directions. The weaker direction (i.e., that with the minor resistant section) is analysed as an equivalent shear wall (i.e., such as a masonry wall subjected to a vertical load and a horizontal force). The seismic force is considered the total weight of each storey level and the maximum shear strength in each direction. The strength of the equivalent shear wall in-plane is calculated by the means of the expression of Turnšek and Čačovič (Eq. (B.1)). The equivalent seismic force is calculated according to the Italian Norm D.M. 16.01.1996 (Eq. (B.2)).

$$\tau_u = A \times \tau_k \sqrt{1 + \frac{\sigma_o}{1.5 \times \tau_k}} \quad (\text{B.1})$$

Where:

τ_u is the ultimate shear strength (kPa);

A is the cross section of the equivalent wall (length $\times$ width); (m^2);

τ_k is the characteristic shear strength (kPa);

σ_o is the normal vertical stress (load divided by wall cross section area).

$$F_s = 0.4 \times W \quad (\text{B.2})$$

Where:

W is the total vertical load on the wall. The Eq. (B.1) is able to be reformulated in function of the characteristic shear strength τ_k and the vertical load σ_o , (considering the permanent and quasi-permanent loads of all storeys above the level of verification), obtaining a coefficient C_{conv} (Eq. (B.3)) that represents the conventional shear strength of the equivalent wall in the less favourable direction, considering the difference of resisting wall area among both principal directions.

$$C_{conv} = \frac{\alpha_0 \times \tau_k}{q \times N} \sqrt{1 + \frac{q \times N}{1.5 \times \alpha_0 \times \tau_k \times (1 + \gamma)}} \quad (\text{B.3})$$

Where:

N is the number of levels above the level of analysis (including it);

τ_k is a reference value of 60 kPa;

$\alpha_0 = A_{min}/A_t$, where A_{min} is the minor of the A_x, A_y wall section directions (XX, YY) and $A_t = A_x + A_y$ in m^2 ; $\gamma = A_{min}/A_{max}$ q is the mean weight of a storey level by unit of covered area, including

the self-weight of walls and diaphragms (Eq. (B.4))

$$q = \frac{(A_x + A_y) \times h \times p_m}{A_t} + p_s \quad (\text{B.4})$$

Where:

h is the mean free height of the stories in m;

p_m is the density of the masonry in kN/m^3 ;

p_s is the weight by area of the diaphragms in kN/m^2 .

The characteristic strength of the masonry is able to be based on experimental evidence or according to local construction codes and/or recommendations, such as the Italian code D.M. 2nd of July 1981, GNDT-SSN. The class for this parameter is given by the ratio, $\alpha = C_{conv}/\bar{C}$ (Table B.3), where the reference value for $\bar{C}$ is 0.4, correspondent to a maximum seismic force in an active seismic region:

Class	Original description (Vicente [2008])	Adjustments for Atlixco, Puebla
A	$\alpha \geq 1.0$	$\alpha \geq 1.0$
B	$0.6 \leq \alpha < 1.0$	$0.6 \leq \alpha < 1.0$
C	$0.4 \leq \alpha < 0.6$	$0.4 \leq \alpha < 0.6$
D	$\alpha < 0.4$	$\alpha < 0.4$

Table B.3: Classes for the parameter BP3.

The reference values for this parameter have been reviewed in order to relate them to Mexican codes and characteristic values found in literature. The values for characteristic shear strength (τ_k), weight by area of diaphragms (p_m) and density of masonry (p_s) were set according to the following principles:

(a) Diaphragms. Values for p_m and p_s . The weight by area of diaphragms (p_s) is composed by a dead load and a live load. The Mexican Code of Construction for Mexico City (Gobierno del Distrito Federal 2017) includes a series of standard live loads (W_a) to be used when analysing seismic design and depend on the use of the building. Since this information is taken from the datasheet, it is possible to accurately associate this value. This value is compared to the values given in Eurocode 1 (European Committee for Standardization 2002), since the latter could lead to more conservative values and in this case has been adopted, as per B.4. The weight by area of the diaphragms was based on the Basic Document of Structural Safety of the Technical code for Construction (Ministerio de Fomento 2009), as per Table B.6.

Datasheet Uses	Mexican Code of Construction for Mexico City Uses	Live Load (kN/m²)	Eurocode 1 Uses	Live Load (kN/m²)
Domestic, Hotel	Housing units: houses, apartments, rooms, hotel rooms, hostels, barrack, jails, hospitals and similar.	1.0	EC1-Housing	1.5-2.0
Government	Offices, studies and laboratories.	1.8	EC1-Medium concentra- tion	3.0-4.0
School	Classrooms.	1.8	EC1-Medium concentra- tion	3.0-4.0
-	Stadiums and meeting places with no individual seats.	3.5	EC1-High concentra- tion	6.0-7.5
Religious, Leisure	Libraries, temples, cinemas, theatres, gym, ballrooms, restaurants, playrooms and similar.	2.5	EC1-Medium concentra- tion	3.0-4.0
Commercial, Mixed	Commerce, factories, storing areas.	3.5 (min)	EC1-High concentra- tion	6.0-7.5
-	Roofing with pending of less than 5%	0.7	EC1- Balconies	2.5-4.0
-	Roofing with pending of more than 5%	0.2	EC1 – Non accessible roofing	0.4
-	Cantilever above a pedestrian path.	0.7	EC1- Balconies	2.5-4.0
-	Garages and parking lots. Only for automobiles.			

Table B.4: Correspondence among the uses stated in the datasheets for Atlixco against the uses and live loads found in the Mexican Code and Eurocode 1. The value for p_m was selected as the most conservative one between both codes.

Systems according to the Basic Document of Structural Safety of the Technical code for Construction	Corresponding diaphragms found in the Catalogue of Atlixco in field F5	Dead Load (kN/m²)
Bidirectional slab total width of less than 0.30m	Timber beam, clay brick and <i>ter-rado</i> .	4.0
Concrete slab of 0.20m	Timber beam and concrete slab	5.0
Bidirectional slab total width of less than 0.30m	Timber beam, clay brick and <i>petatillo</i>	4.0
Concrete slab of 0.20m (Ministerio de Fomento 2009)	Concrete slab	5.0
Bidirectional slab total width of less than 0.30m	Timber beam and clay brick	4.0
Concrete slab of 0.20m (Ministerio de Fomento 2009)	Concrete beam and clay brick	5.0
Catalan covering. (Ministerio de Fomento 2009)	Catalan vault	2.5
Metallic sheet with concrete slab. Total width 0.12m	Metallic beam and metallic sheet	2

Table B.5: Dead load associated to the materials.

(b) Masonry walls. Values for p_s and t_k . The characteristic values for the density and shear strength for diverse typologies of masonry may be found in the works of Vicente Vicente [2008]. Despite the semantic divergences found in the datasheets for Atlixco, the descriptions have been framed in similar masonry typologies in order to provide characteristic values (Table B.6).

Material (Vicente [2008])	Catalogue of Atlixco, Field F4	Density p_s (Vicente [2008])	Characteristic strength t_k Vicente [2008]
Stone (granite)	Stone masonry	26-27	40
Stone (poor condition)	Stone masonry and adobe.	26-27	20
Round stone masonry	Adobe, round stone and clay brick.		40
Irregular masonry of volcanic stone	Stone masonry and brick masonry.	18	20

Table B.6: Dead load associated to the materials.

Maximum distance between walls (BP4). This parameter describes the role that orthogonal walls have on constraining an out-of-plane failure of a façade wall. This parameter is assessed based on the comparison between the width of the façade wall and two distances between effective bond or connection to walls or floors (support conditions): h_0 (the height between storeys or storey / roof efficiently connected to the façade), and L , the largest distance between orthogonal walls efficiently connected to the façade (see Table B.7).

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$\left(\frac{h_0}{s}\right)_{max} \leq 10; \left(\frac{L}{s}\right)_{max} \leq 15$	This criterion has been adopted since the datasheets provide the necessary data in fields F13 and F4.
B	$10 < \left(\frac{h_0}{s}\right)_{max} \leq 15; 15 < \left(\frac{L}{s}\right)_{max} \leq 18$	
C	$15 < \left(\frac{h_0}{s}\right)_{max} \leq 20; 18 < \left(\frac{L}{s}\right)_{max} \leq 25$	
D	$\left(\frac{h_0}{s}\right)_{max} > 20; \left(\frac{L}{s}\right)_{max} > 25$	

Table B.7: Classes for the parameter BP4.

Number of floors (BP5). This parameter associates an increasing vulnerability according to the number of storeys of the building, given that the number of storeys is proportional to height and that tall masonry constructions are more likely to present structural irregularities (such as out-of-plane deformations). The classification criterion is given in Table B.8).

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Building with 1 storey (i.e., ground level)	This criterion has been adopted since the datasheets provide the necessary data. No buildings with more than 2 storey levels were found in Atlixco and, in fact, are very uncommon in Mexican historical centres. Information of field F7.
B	Building with 2 or 3 storeys	
C	Building with 4 or 5 storeys	
D	Building with more than 6 storeys	

Table B.8: Classes for the parameter BP5.

Location and soil conditions (BP6). Three factors are considered and combined in this parameter: the topographic environment of the building (slope, in %), type and consistency of the soil and the presence of foundations and their eventual difference of footing levels, Δh . Due to the complexity for obtaining detailed information for every single building, the methodology accepts that it is possible to assume a reasonable hypothesis for all the buildings in a region based on the available information on the typologies and/or surveys. This parameter considers that the soil can be framed in three different types according to the criteria of the Eurocode 8: Rock (soil type A); loose and not impulsive soils (types B and C); and loose and impulsive soils (types D and E). The combinations of soil types, foundations properties and slope can be found in Table B.9).

Class Original description (Vicente [2008])					Criteria for Atlixco
	Soil type	Foundations	Slope (%)	Δh	
A	A	Indifferent	$p \leq 10$	Indifferent	The assessment of this parameter results problematic in Atlixco since the information regarding the foundations is not available. In order to keep a conservative approach, the foundations were considered as inexistent. The slope was also generalised according to the information provided by the GIS Topographic of the city (INEGI - Instituto Nacional de Estadística y Geografía 2019). No buildings are located in sloped areas of more than 10%. The type of soil was taken from the classification of CENAPRED (Centro Nacional de Prevención de Desastres 2006) and the Municipal Geology Map (Atlixco 2014). The city corresponds to a deposit of dense sands, gravel and clays, equivalent to the soil class B according to Eurocode 8 classification. Then, all the buildings were classified as B for this parameter (Soil type B, with no foundations, a slope of less than 10% and a difference Δh different to zero).
C	B, C	Yes (stone)	$p \leq 10$	$\Delta h = 0$	
	B, C	No	$p \leq 10$	$\Delta h = 0$	
B	A	Indifferent	$10p \geq 30$	Indifferent	
	B, C	Yes (stone)	$p \leq 10$	$0 < \Delta h = 0 \leq 1$	
	B, C	Yes (stone)	$10p \leq 30$	$\Delta h = 0 \leq 1$	
	B, C	No	$p \leq 10$	$0 < \Delta h = 0 \leq 1$	
	B, C	No	$10p \leq 20$	$\Delta h = 0 \leq 1$	
C	A	Indifferent	$10p \leq 50$	Indifferent	
	B, C	Yes (stone)	$30p \leq 50$	$\Delta h = 0 \leq 1$	
	B, C	No	$20p \leq 30$	$\Delta h = 0 \leq 1$	
	D, E	Yes	$p \leq 50$	$\Delta h = 0 \leq 1$	
	D, E	No	$p \leq 30$	$\Delta h = 0 \leq 1$	
D	A	Indifferent	$p > 50$	Indifferent	
	B, C	Yes (stone)	$p > 50$	Indifferent	
	B, C	Yes (stone)	Indifferent	$\Delta h = 0 > 1$	
	B, C	No	$p > 50$	Indifferent	
	B, C	No	Indifferent	$\Delta h = 0 > 1$	
	D, E	Yes	$p > 50$	Indifferent	
	D, E	Yes	Indifferent	$\Delta h = 0 > 1$	
	D, E	No	$p > 30$	Indifferent	
	D, E	No	Indifferent	$\Delta h = 0 > 1$	

Table B.9: Classes for the parameter BP6.

Aggregate position and interaction (BP7): When the building is part of an aggregate or row building construction and share load bearing walls which is common in adjacent constructions, it becomes necessary to characterise the role of this interaction on the seismic behaviour of the single building. The most favourable condition is that of a building in the middle of two adjacencies with a coincidence on the diaphragms. When the horizontal diaphragms are not at the same height, a potential pounding effect should be considered. The class criteria for this parameter can be found in Table B.10.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Building with 1 storey (i.e., ground level)	This criterion has been adopted since the datasheets provide the necessary data. Information is found in fields F11 and F13.
B	Middle of the block. Coincident diaphragms.	
	Isolated construction	
C	In the corner of a block. Coincident diaphragms	
D	In the corner of a block. Non coincident diaphragms	
	In the end of a block.	

Table B.10: Classes for the parameter BP7.

Plan configuration (BP8): The structural performance of the building is conditioned by its geometrical regularity. The eccentrical volumes are meaningful for promoting significant stiffness differences and dynamic modes among the sections of a construction. In order to assess the irregularity of a construction, two ratios are considered. These analyses are based on discriminating and understanding the plan of the building as a dominant regular figure and the eccentricities associated to this regular figure. A first ratio $\beta_1 = a/L$ assesses the shortest (a) and the largest (L) sides of the regular part. The ratio $\beta_2 = b/L$ involves the largest side of the regular part (L) and the length of the side of eccentric section perpendicular to L (b), as shown in Figure B.1 The most unfavourable classification of the two potential assessments is assigned, according to Table B.11.

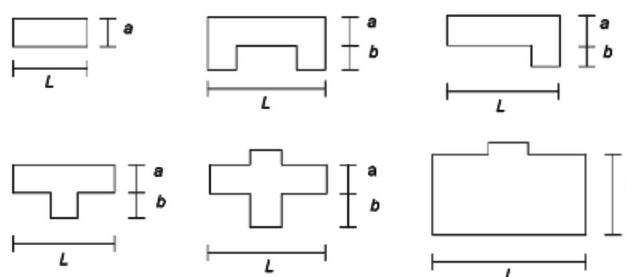


Figure B.1: Examples of L , a and b for multiple plan configurations.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$\beta_1 \geq 0.75, \beta_2 \leq 0.1$	This criterion has been adopted since the datasheets provide the necessary data. A potential limitation, however, was found because of the frequent use of the symmetrical central patio layout. Information is found in field F12.
B	$0.5 \leq \beta_1 < 0.75, 0.1 < \beta_2 \leq 0.2$	
C	$0.25 \leq \beta_1 < 0.5, 0.2 < \beta_2 \leq 0.3$	
D	$\beta_1 < 0.25, \beta_2 > 0.3$	

Table B.11: Classes for the parameter BP8.

Height regularity (BP9): This parameter assesses the variation of surface area between two consecutive storeys, implicitly inferring over the difference of stiffness that this variation of area can imply. The simplified approach for this assessment is through the percentual ratio $\pm \Delta M / M$ between the mass of two consecutive floors. Given an assumption of homogeneity of mass distribution in a building, it is possible to alternatively assume a simpler assessment based on the area ratio $\pm \Delta A / A$. Some modifications for this first level approach for classification are the presence of some solutions, such as a width reduction of the thickness of the walls in height, the presence of a ground floor gallery or the presence of towers. Furthermore, the contextualisation of the building in a series of constructions may imply a downgrade of the assessment just as discussed for parameter BP7. The selected grade is the worst of the applicable situations summarised in Table B.12.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$\Delta A/A < 10\%$ or $\pm \Delta M/M < 10\%$ Building in the middle of other two with a height difference of less than $\frac{1}{2}$ of a storey. Isolated construction	This criterion has been adopted since the datasheets often provide the necessary data for classification. Nevertheless, the datasheets only consider the architectonic plan corresponding to the ground floor of the construction (field F12), limiting the assessment of ΔA . In most of cases it was possible to provide a classification based on the pictures and the visual information available in sources such as Google Maps and/or Google Earth.
B	$10\% < \Delta A/A < 20\%$ or $10\% < \pm \Delta M/M < 20\%$. Building with a tower with a height of less than 10% of the total height of the building. Building with a gallery or arcade of less than 10% of the area of the level. Building adjacent to one or two taller constructions with a height difference of more than $\frac{1}{2}$ of a storey.	
C	$20\% < \Delta A/A < 30\%$ or $20\% < \pm \Delta M/M < 30\%$. Building adjacent to a shorter construction with a height difference of more than $\frac{1}{2}$ of a storey. Building with a tower with a height between 10% and 40% of the total height of the building Building with a gallery or arcade of between 10% and 20% of the area of the level.	
D	$\Delta A/A > 30\%$ or $\pm \Delta M/M > 30\%$ Building adjacent to two shorter constructions with a height difference of more than $\frac{1}{2}$ of a storey. Building with a tower with a height of more than 40% of the total height of the building. Building with a gallery or arcade of more than 20% of the area of the level.	

Table B.12: Classes for the parameter BP9.

Wall façade openings and alignment (BP10): The area and vertical or horizontal misalignment of openings influences the in-plane and out-of-plane failure mechanisms. The misalignment has a negative effect on the behaviour and performance of the constructions, even for vertical permanent loads, favouring concentration of stresses, which can lead to meaningful seismic cracking and instability of wall piers and spandrels. The classification criterion for this parameter is presented in Table B.13.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Regular dimensions and aligned in height.	This criterion has been adopted since the datasheets often provide the necessary data for classification, namely through photographs and drawings of the façades (field F13).
B	Regular or irregular dimension horizontally misaligned in more than $\frac{1}{2}$ of their height.	
C	Regular or irregular dimension vertically misaligned in more than $\frac{1}{2}$ of their height.	
D	Regular or irregular dimension totally misaligned. Relatively large openings at any level of the construction	

Table B.13: Classes for the parameter BP10.

Horizontal diaphragms (BP11): The conditions of the connections between floor diaphragms and walls as well as their ability for efficiently transmit vertical loads to the walls (and the foundations) influence the global behaviour of the buildings. The key aspects of this behaviour are the stiffness of the diaphragms and the quality of their connection to the walls. A poor connection may promote situations such as distortion, deformations, and unstable support conditions. A downgrade of the classification is considered if there is evidence of decay. The criteria for this parameter can be found in Table B.14.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Rigid or semi-rigid and well connected.	The assessment of this parameter was mostly based on two sources. The first one is the description of diaphragms offered in datasheets (field F5). Every description was associated to a stiffness criterion (rigid, semi-rigid or flexible). The existence of decays was associated to the conservation state (field F8) declared in the datasheet (“good” =no decay; “regular” or “bad” =decay), supported by visual information (if available). The quality of the connections was classified according to the grade of BP1: (A, B=well connected; C, D=poorly connected).
B	Flexible and well connected. Rigid or semi-rigid and well connected, but with signs of decay*	
C	Rigid or semi-rigid and poorly connected. Flexible and well connected, but with decays*	
D	Flexible and poor connected.	
*	Weakness in the regions of contact with the vertical structure, signs of deformation, rotting or shrinkage, or lack of safety for circulation.	

Table B.14: Classes for the parameter BP11.

Roofing system (BP12): This parameter assesses the weight, span and perimetral support conditions. The effects of the roofing system include a potential horizontal impulse onto the walls, favouring out-of-the plane failure. This parameter assesses if there is a perimetral strap or beam that contains the horizontal thrust of the roofing system, the presence of tensile elements for restraining horizontal thrusts and considers the impulsive nature and conservation state of the roofing structure (good, medium and bad). The impulsiveness of the roofing system is based on three potential situations:

a) Non impulsive roofing systems. Plane structures, trusses, and gabled roofs with tie-rods to absorb horizontal stresses. b) Slightly impulsive roofing systems. Gabled roofs without tensors cancelling horizontal stresses and a span/height proportion $l/h < 20$. c) Impulsive roofing systems. Gabled roofs without tie-rods cancelling horizontal stresses and a span/height proportion $l/h > 20$.

The matrix for deciding the classification of this parameter is presented in Table B.15.

Class	Original description (Vicente [2008])			Criteria for Atlxco
	Impulsive nature	Perimetral straps/beam	State of conservation	
A	Non imp.	At least one	Good	This criterion has been adopted since the datasheets often provide the necessary data for classifying, namely through the description of the field F6. The state of conservation was directly taken from the field F8 of the datasheet. The existence of perimetral straps or beams of tensile-resistant elements was not observed in the case of study.
	Non imp.	At least one	Bad	
B	Non imp.	None	Good	
	Slightly imp.	At least one	Good	
	Non imp.	At least one	Very bad	
	Non imp.	None	Bad	
C	Slightly imp.	At least one	Bad	
	Slightly imp.	None	Good	
	Impulsive	At least one	Good	
	Impulsive	At least one	Bad or very bad	
D	Non imp.	None	Very bad	
	Slightly imp.	None	Bad or very bad	
	Impulsive	At least one	Bad or very bad	
	Impulsive	None	Indifferent	

Table B.15: Classes for the parameter BP12.

Fragilities and conservation status (BP13): This parameter departs from the identification of evident fragilities and damages that may magnify seismic damages, precipitating some mechanisms. The most important damages to be identified are cracks, deformations and evidence of disintegration. The criterion for this parameter is summarised in Table B.16.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Walls in good conditions with no visible damage.	This parameter was graded by analysing the information available in fields F3, F4, F8, F14 and F15. Most of damages are mentioned in the description of the building but are also visible in the corresponding photographs. It is important to note that for all the datasheets that were surveyed after the 2017 earthquake, it was necessary to consult pre-event photographs, namely those found in the Google Maps database. The descriptions on the datasheets explicitly differentiate the damages occurred due to the 2017 earthquake.
B	Small and non-generalised cracks (<0.5mm width). Signs of decay due to humidity in masonry and timber elements. Cracks in coatings that do not penetrate the support.	
C	Generalised cracks (2-3mm width). Regular state of conservation of the walls. Serious deformations in the staircases and floor diaphragms; diagonal cracks in internal walls and cracks in the middle of openings.	
D	Walls with serious decay and cracking, even if it is not generalised. Decays that evidence a loss of strength. Cracks in sensitive locations, such as corners (e.g., due to disconnection between walls). Damages in the interfaces between roofs and walls, displacement of floor diaphragms. Rotting and decay of timber beams. Out-of-plane deformations of the walls.	

Table B.16: Classes for the parameter BP13.

Non-structural elements (BP14): This parameter assesses the effect that certain elements impose for inducing damages in the structure. Elements such as cornices, parapets, balconies, or other external elements that are connected to the structure and promote load eccentricities on the façade walls. The assessment criterion is based on the mass of the elements and connections, as presented in Table B.17.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Building with no cornices, parapets or suspended elements.	This parameter is able to be classified based on the images of field F13.
B	Presence of well-connected cornices, light and small chimneys. Balconies integrated to the floor structure or walls.	
C	Presence of small external elements with a poor connection to the structure. Coatings and/or finishing generalised and well attached or localised and poorly attached.	
D	Elements of considerable weight (chimneys, water reservoirs on the rooftop, mechanical equipment attached to the walls) poorly connected to the structure. Balconies with poor connection to horizontal elements, namely those that were added to the original building. Large and poorly connected false plafond.	

Table B.17: Classes for the parameter BP14.

Geometry of façade (FP1). This parameter assesses the ratio of the base length (B) and height (H) of the façade. The thresholds are those of Table B.18.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$H/B < 0.40$	This parameter is able to be graded based on the images of the field F13.
B	$0.40 \leq H/B < 0.60$	
C	$0.60 \leq H/B < 1.00$	
D	$H/R > 1.00$	

Table B.18: Classes for the parameter FP1.

Maximum slenderness (FP2). Slender walls are more likely to have an out-of-plane failure. Thresholds for grading the presented in Table B.19, considering the quotient of the height (H) divided by the width of the wall (S).

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$H/S \leq 9$	This parameter is able to be graded based on the images of the field F13 and the thickness reported in F4.
B	$9 \leq H/S \leq 15$	
C	$15 \leq H/S \leq 20$	
D	$H/S > 20$	

Table B.19: Classes for the parameter FP2.

Area of openings (FP3). The response of a masonry wall panel is influenced by the configuration and dimension of openings since they determine the on-plane failure mechanisms. This parameter is easily assessed by the ratio between wall and opening areas, as expressed in Table B.20.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Area of openings of less than 20%	This parameter is able to be graded based on the images of the field F13.
B	Area of openings of less than 35%	
C	Area of openings of less than 60%	
D	Area of openings of more than 60%	

Table B.20: Classes for the parameter FP3.

Misalignment of openings (FP4). The logic that supports this parameter is comparable to BP10. Consequently, the criteria are similar, as summarised in Table B.21.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	Regular dimensions and aligned in height.	This parameter is able to be graded based on the images of the field F13.
B	Regular or irregular dimension horizontally misaligned in more than $\frac{1}{2}$ of their height.	
C	Regular or irregular dimension vertically misaligned in more than $\frac{1}{2}$ of their height.	
D	Regular or irregular dimension totally misaligned. Relatively large openings at any level of the construction	

Table B.21: Classes for the parameter FP4.

Interaction between continuous façades (FP5). This parameter was not considered in the proposal of Vicente Vicente [2008], but has been included in the calibration of Ferreira et al. [2017a] and was then adapted by Aguado [2017]. The grades corresponding to this parameter assess the potential pounding effect of contiguous constructions, similarly to the parameter BP7. The criterion for grading is explained in Table B.22.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	In the middle of two façades of the same height.	This parameter is able to be graded based on the images of the field F13 and the localisation plan of F11. A limitation found for this parameter is the attachment to only one taller façade.
B	Contiguous to a façade of the same height and a shorter one.	
C	Contiguous to two shorter façades.	
D	Contiguous to only one, shorter façade.	

Table B.22: Classes for the parameter FP5.

Quality of materials (FP6). This parameter corresponds to parameter BP2. Therefore, the grading criteria is the same. A similar situation occurs with the **parameter FP7**, State of conservation, that has direct correspondence to parameter BP13.

Replacement of the original flooring system (FP8). This parameter was also introduced in the calibrations of Aguado [2017] and Ferreira et al. [2017a]. Describes the proportion of horizontal diaphragms that were re-placed by reinforced concrete structures (in percentage P), accepting that this replacement is a source of damage for masonry walls. The grades considered by Aguado are summarised in Table B.23.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	$0 \leq P < 25\%$	Even if there is no quantitative information for grading this parameter, the descriptions found in fields F5, F6, F14 and F16 supported a guess for assigning a class.
B	$25 \leq P < 50\%$	
C	$50 \leq P < 75\%$	
D	$75 \leq P < 100\%$	

Table B.23: Classes for the parameter FP8.

Connection to orthogonal walls (FP9). An efficient connection between the façade and the perpendicular walls minimises the out-of-plane mechanisms. The assessment criteria for this parameter are summarised in Table B.24.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	The façade is well connected to the orthogonal walls, diaphragms, and roofing structures by the means of metallic perimetral straps, tie rods and well locked masonry. These connections exist in all orthogonal connections.	The assessment of this parameter is based on BP11.
B	Masonry well locked in the corners, with no signs of fragility. Conditions of grade A exist in some corners.	
C	There is no good connection between the façade and the orthogonal walls. However, there are no signs of fragility. Conditions of grade B exist in some corners.	
D	The façade is deformed with an elevated risk of imminent failure (cracked according to mechanism patterns). Detachments and cracking in corners and orthogonal interfaces.	

Table B.24: Classes for the parameter FP9.

FP10. This parameter is similar to FP9 but addressed to the connections between the façade wall and the diaphragms and roofing structures. While parameter FP9 considers a qualitative grading, FP10 gives a grade based on the proportion of efficient connections (in percentage e). This parameter complements parameters BP11 and BP12, involving the decays considered for BP11. The grading is given as explained in Table B.25.

Class	Original description (Vicente [2008])	Criteria for Atlxco	
A	$e \geq 75\%$	Even if there is no quantitative information for grading this parameter, the descriptions found in fields F5, F6, F14 and F16 supported a guess for assigning a class.	
B	$e \geq 75\%$, with decays* $50\% \leq e < 75\%$		
C	$50\% \leq e < 75\%$, with decays* $25\% \leq e < 50\%$		
D	$25\% \leq e < 50\%$, with decays* $e < 25\%$		
*	Weakness on the regions of contact with the vertical structure, signs of deformation, rotting or shrinkage, or lack of safety for circulation		

Table B.25: Classes for the parameter FP10.

Impulsive nature of roofing system (FP11). This parameter is equivalent to BP12. Therefore, the grading criteria is the same.

Elements connected to the façade (FP12). This parameter is similar to BP14, but the criterion for grading is slightly different since it only involves elements of the façade. The most common situations of attached elements that may condition the overturning of the façade is summarised in Table B.26.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	There are no elements attached to the façade.	Based on the images (field F13).
B	Some light elements, such as lights, signals, light roofs, etc.	
C	Medium weight elements attached to the façade: equipment, air-conditioned devices, etc.	
D	Existence of balconies or other heavy elements connected to the façade.	

Table B.26: Classes for the parameter FP12.

Improving elements (FP13). This parameter was added in the calibrations of Aguado [2017] and Ferreira et al. [2017a], recognising the role that some elements in contact to the external side of the façade have for mitigating out-of-plane failures, regardless of their explicit structural function. Some common elements are mentioned in Table B.27.

Class	Original description (Vicente [2008])	Criteria for Atlixco
A	There are no external elements.	Based on the images (field F13).
B	Presence of exterior stairs, arches, giants, etc.	
C	Explicit reinforcement through the use of reinforced plasters.	
D	Strengthening actions by the means of elements such as buttresses or similar.	

Table B.27: Classes for the parameter FP13.