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A Risk Index for the Structural Diagnosis of Masonry Heritage (RISDiMaH)

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Abstract

Experts responsible for the safety evaluation of unique masonry heritage structures usually need to weigh information from various diagnosis activities before deciding the best course of action for preservation. Typical sources of valuable information are historical and in-situ surveys and inspections, minor and non-destructive testing, structural health monitoring, and structural analysis, among others. Due to the complexity of the problem and singular aspects of monuments, these decisions are challenging and often made solely on the basis of expert judgement. A systematic risk assessment procedure is proposed involving the computation of two indices to facilitate the decision-making process: an index related to the estimated risk of damage, and another to the uncertainty behind this estimation. Results from applying the procedure to several case studies are provided to demonstrate its usefulness.

Keywords: `Structural analysis, Structural Health Monitoring (SHM), Non-Destructive Testing (NDT), Minor-Destructive Testing (MDT), Risk assessment, Decision analysis, Multi-Criteria Decision Making (MCDM)`

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1. Introduction

Recent years have been marked by significant advances in analysis, inspection, testing, and monitoring techniques applied to the diagnosis of masonry heritage structures. Most of these developments are motivated by the fact that an accurate evaluation of the current structural condition is critical to ensure the survival of such structures. Despite these advances, the diagnosis of unique monuments still remains a challenging task. This is mainly due to the large number of uncertainties linked to the geometry of the structure, to the interaction among different parts, as well as to the mechanical, physical and chemical properties of the material. To add to this complexity, the need to protect heritage value often prevents the extraction of a comprehensive set of samples to characterise the material. Modern standards for new structures conservatively account for such uncertainties, related to the structural scheme or to material characteristics, through the application of safety factors. Although this approach is adequate for new structures, where safety can be increased with modest increases in member size, it cannot be applied to heritage structures because requirements to improve capacity can lead to the loss of historic fabric or to changes in the original structural conception. Consequently, the principle of minimum intervention is preferred for heritage structures [1]. This requires adopting a flexible and broad approach in order to be able to relate the remedial measures more clearly to the actual structural behaviour. In other words, faced with the impossibility of adopting a conservative approach, the diagnosis task is crucial, because the actual structural behaviour needs to be well understood to design appropriate remedial measures, if any.

As a result, the decision making task on remedial measures becomes particularly difficult, since the very nature of the problem entails the need for an accurate diagnosis in the face of strict limitations on specimen extraction for testing. As a consequence of this challenge, there is a growing body of literature

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Abbreviations: SIEA, Standardised Initial Expert Appraisal; LoK, Level of Knowledge; DR, Damage Risk; DV, Damage Vulnerability.

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Email addresses: `nirvan.makoond@upc.edu` (Nirvan Makoond), `luca.pela@upc.edu` (Luca Pelà), `climent.molins@upc.edu` (Climent Molins) that has examined and evaluated the application of new technologies, minor destructive tests (MDT), and non-destructive testing (NDT) to facilitate the diagnosis of heritage structures. Such techniques can now be applied to provide information on a wide variety of aspects that are key to an accurate diagnosis. Applications exist to obtain more accurate representations of the geometry and damage [2–8], to estimate material properties [9–17], to characterise material quality and variability [17–22], to evaluate actual loading and boundary conditions [17, 23–26], and even to monitor the structural response [27–35]. Similarly, there is a considerable amount of literature on numerical modelling [36–47] and other structural analysis tools [48–52] that can be used to provide vital information for diagnosis and for accurately assessing the damage vulnerability of masonry heritage structures. As a result, depending on cost limitations and on the complexity of the heritage structure, an expert responsible for structural diagnosis can nowadays choose from a wide variety of tools to inform decisions on further investigations or interventions. Subsequently, relevant information and results from all selected diagnosis activities should be used to assess the vulnerability of the structure.

Before making any recommendations on interventions or further investigation, experts also have to take into consideration other risk components not directly related to the vulnerability of the structure to damage. These include factors related to the exposure level, such as the cultural value associated to the structure, or to the hazard level, such as the probability of occurrence of a high intensity catastrophic event. This results in a complex decision problem involving multiple divergent criteria. Decisions requiring such assessment can often benefit from improved objectivity and transparency through the application of formal decision analysis and multi-criteria decision-making (MCDM) techniques [53–56].

In fact, there are several examples in literature of applications of MCDM techniques for general vulnerability or risk assessment to facilitate decisions on preventive conservation at the urban or territorial scale [57–61]. Although these proposed MCDM tools all differ in terms of the specific criteria they employ, they all share some common points. Firstly, they are all indicator-based and rely on one of the simplest and most widely used MCDM techniques known as Simple Additive Weighting (SAW). This technique consists in the addition of normalised criteria scores weighted by corresponding relevance factors defined in a previous step. The popularity of this technique stems from its very simple and transparent calculation procedure and from the fact that it is very intuitive for decision makers. Naturally, this simplicity comes at the price of strong assumptions on the decision problem that need to be considered carefully. The additive value model behind SAW means that attributes are assumed to be preferentially independent. This means that preference regarding the value of one attribute is not influenced by the values of other attributes at the same hierarchy level of the decision problem [62, 63]. In addition, SAW can only deal with maximising positive defined criteria, meaning that any minimising criteria need to be properly converted to maximising ones [55, 56]. In spite of these limitations, successful applications of the technique for prioritisation of preventive conservation at the territorial level is a clear indicator that it can be adapted to provide meaningful insights for decisions on heritage structures. Some authors have even attempted to complement their proposed index representing global damage risks with a decay model to predict the service life and the evolution of maintenance costs over time [58].

With respect to masonry structures, although there are some examples of MCDM applications for the assessment of general damage vulnerability at a territorial scale, applications that have had the greatest success in terms of widespread use in practice specifically involve the evaluation of seismic vulnerability. This is a direct consequence of the increase in losses caused by natural catastrophes in the last few decades and the subsequent need to asses and prioritise vulnerability among large stocks of existing buildings in earthquake-prone regions. In one of the earliest applications of MCDM techniques to this problem, the seismic vulnerability is expressed through a *Vulnerability Index* computed from 10 key attributes using SAW [64]. The choice of the specific attributes as well as the index formulation were based on a vast set of post-earthquake damage observations together with expert judgements. This method and adaptations of it have been applied extensively in Italy in the past few decades [65]. The method was also combined with another one known as the *Macroseismic Method* [66] for the seismic vulnerability assessment of masonry structures in a historical city centre in Portugal [67]. Based on available data, changes were made to attributes and weights of the index developed for use in Italy. This hybrid method has in turn been further modified for the seismic vulnerability assessment of vernacular architecture [68]. Such methods have also been adapted and applied to other historical city centres [69, 70]. Nowadays, results from such applications are even used in broader risk assessment frameworks to estimate losses in future earthquakes, to compare the impact on estimated loss of possible retrofitting solutions, and to plan emergency response [65, 71].

The research work on seismic evaluation leading to the development of some of the methods presented in the previous paragraph has greatly improved scientific and technical knowledge on the seismic performance of masonry heritage structures. In fact, much of this work has been built upon to elaborate the Italian "Guidelines for evaluation and mitigation of seismic risk to cultural heritage" [72, 73], which was formally adopted in 2011. The Guidelines introduce three evaluation levels whose application depends on the seismic safety analysis needs. The simplest evaluation level relies on computing a *Seismic Safety Index* based on qualitative information and very simplified mechanical models, the second relies on kinematic analyses of individual macro elements, and the third involves the global evaluation of the seismic response of the building. The simplest evaluation level is deemed as only being sufficient for evaluating the vulnerability of cultural heritage on a territorial scale. However, even for the case of designing strengthening interventions, it is still specified that the *Seismic Safety Index* can be "an important quantitative element to consider along with others in a complex qualitative judgement that takes into consideration conservation criteria, the desire to protect the building from seismic damage, and safety requirements in relation to fruition and function". The guidelines developed as part of the PERPETUATE European research project [74] clearly aims to address this required complex qualitative judgement for seismic safety assessment through improved systematisation. The guidelines propose a methodological path which can be broadly summarised in three steps. The first is mainly concerned with the classification of assets, the characterisation of seismic hazard, and the definition of target performance levels. The second step involves finalizing structural models for seismic analysis and performing verifications while the final step deals specifically with making rehabilitation decisions.

In many natural-hazard-prone areas, the assessment of seismic risk alone might not be sufficient for the prioritisation of disaster risk reduction and resilience-enhancing strategies. To address this, some researchers have recently proposed a multi-hazard risk prioritisation index for cultural heritage assets which was calibrated and applied to 25 heritage buildings in the Philippines [75]. The computation of the index relies on data collected through a standard rapid-visual-survey form. Two separate risk prioritisation indices related to seismic and wind hazards are first computed. In this particular application [75], the multi-hazard risk prioritisation index was calculated as the Euclidian norm of the vector with single-hazard prioritisation indices as components. This means that the single-hazard risk indices need to have the same range of variation and that the multi-hazard risk index will be characterised by a different range. Nevertheless, the authors do mention that combination weights can be used instead of the Euclidean norm because the relative effect on the built environment of two different catastrophic events can change completely depending on the return period considered.

It is clear that risk assessment of masonry heritage structures at the territorial level has benefited greatly from the application of MCDM methods. In addition, it is undeniable that good decisions in conservation require the availability of appropriate information. This is evidenced by the development of integrated information systems based on well-defined concepts of preventive conservation to support risk management decisions for some UNESCO world heritage sites [76–78]. However, hardly any attempt has been made to apply decision analysis methods to assess the risk of structural damage in unique complex monuments. One of the main challenges to their application lies in the unique nature of each structure and the individual characteristics that shape their risk landscapes. Furthermore, as previously mentioned, the assessment of the damage vulnerability of unique monuments can be informed by a wide variety of diagnosis activities including NDT and structural health monitoring (SHM). Naturally, it is currently unfeasible to carry out many of these activities when conducting vulnerability assessment at a territorial scale. Consequently, most of the aforementioned methods developed for risk and vulnerability assessment at the territorial scale rely solely on information that can be obtained from technical visual inspections and geometry surveys. Therefore, because vulnerability is a key component of risk [79], it can be expected that direct application of these methods for the risk assessment of a unique monument can only provide a very limited picture of the risk landscape that needs to be considered for decisions on preventive measures.

As such, any comprehensive risk assessment process for unique monuments should consider information from all relevant diagnosis activities carried out. This only adds to the difficulty of applying standard decision analysis methods since the suitability of different activities and the relative importance of the information they provide for global damage vulnerability assessment can change depending on the specific characteristics of different structures. In fact, as a result of the large heterogeneity across the global masonry building stock and the potential complexity of the diagnosis task, there have been very few attempts at developing systematic diagnosis decision support tools for masonry structures. Two notable tools have been developed which guide the user to possible causes of observed damage from visual inspections [80, 81]. Both can be considered as expert systems that rely on extensive damage databases together with the systematization of expert diagnostic knowledge through hierarchical decision trees. One of these methods, initially named *Masonry Damage Diagnostic System*, was designed specifically for evaluating the possible causes of degradation in brick masonry structures [80], and could even incorporate laboratory results to refine the diagnosis. One of the aims behind this inclusion was to prove the interest of different analysis types and to stimulate the use of proper diagnosis activities. Applications of this expert system have produced very satisfactory results and revealed that the increase of systematisation in the diagnosis process forces users to think through the problem and facilitates the collection of information from different partners and experts in a structured way [80]. This diagnostic system was later expanded to include more materials, like plasters and natural stone [82], and eventually developed into an online tool called *Monument Diagnosis and Conservation System* [83, 84]. Although these expert systems can help in the identification of specific damage causes, they cannot take into consideration information from structural analysis, SHM, or NDT. Moreover, the diagnosis task they address is only a preliminary task before safety and subsequent vulnerability assessment.

Given the unique characteristics of individual monuments, any systematic application of MCDM techniques to assist decision-making on preventive conservation should be able to account for the fact that outcomes from various diagnosis activities will have a different impact on vulnerability assessment depending on specific conditions of each structure. It is also important to note that any assessment of safety can be seriously affected by the uncertainty attached to the data, laws, models, and assumptions used in the research [1]. The recognition of uncertainty allows decision-makers to assess the limitations of available information and to take the best decision with respect to resource allocation for risk mitigation. Therefore, in order to make better decisions, it is important to include information on the level of uncertainty in the assessment and decision-making process [76]. For the case of masonry heritage structures, detailed investigations including NDT and SHM can greatly help to reduce the uncertainty of conclusions derived from structural analysis and subsequent vulnerability assessment. In fact, this has been recognised in the aforementioned Italian and PERPETUATE guidelines [73, 74]. In both cases, different confidence factors are applied to specific parameters of the models used to inform seismic vulnerability assessment based on the extent and depth of surveys performed to improve the level of knowledge on the structural condition.

The current research work aims to develop specific MCDM tools that can be applied to unique masonry heritage structures to assist experts and professionals in the evaluation of damage risk. The tools are intended to improve objectivity, clarity and transparency in the decision process leading to resource allocation for risk mitigation. Specifically, two indices are proposed that can be used to gauge the level of knowledge on the actual structural condition and the associated damage risks. The input data for computing both indices is derived from answers to standard questions that need to be completed by the person responsible for structural diagnosis. Questions used to feed the indices include essential and optional ones. Essential questions need to be answered following the initial history, geometry, and damage survey. Since optional questions relate to the outcome of specific diagnosis activities, they can only be answered if these are carried out. Both indices are computed using SAW based on specifically designed hierarchical trees of the criteria that influence the level of knowledge and the damage risk. A novel modification is proposed to allow the relative importance of information from different activities to change depending on ratings and rankings that have to be provided as answers to certain essential questions. It is important to note that the proposed indices are not meant to automate decisions or to substitute any specific structural safety verification, but rather to contribute to increased systematisation in the decision-making process and to ensure that all relevant information from complementary investigations are considered. As such, effective use of the MCDM tools requires that the answers to standard questions be provided by experts or by professionals with sufficient experience and knowledge on the structural diagnosis of masonry heritage. Naturally, for the index values to be meaningful and useful for decision-making, they have to be evaluated within the framework of a systematic risk assessment procedure based on well-defined scientific principles.

A proposal for such a risk assessment procedure is first presented to provide a general understanding of the mechanisms used to compute and update index values. Subsequently, a brief description is given of the standard questions whose answers are the main input to both indices. The specific criteria and hierarchical structures of the level of knowledge and damage risk indices are then elaborated. Following this explanation, one of the most useful outcomes for decision-making from applying the proposed risk assessment methodology is shown. This involves the automatic generation of a list of relevant diagnosis activities ordered according to their remaining possible contribution to the level of knowledge index. A decision grid with ranges of the proposed indices is then presented to demonstrate how the method can help to improve objectivity and clarity in the decision process. Finally, applications to four case-studies are presented before stating the main conclusions of the research.

2. Risk assessment methodology

In the context of this research, risk assessment refers to the identification, characterisation, and evaluation of the risk of structural damage occurring in a unique masonry heritage structure. The main aim of such a procedure is to determine the most suitable course of action for best preserving the structure. Given the particular characteristics of these structures and the need for minimum intervention, it is now widely accepted that the best form of therapy is a preventive conservation approach, whereby structural condition, risks, and threats are periodically monitored [1, 76, 78, 85, 86]. Within the proposed risk assessment framework, as previously mentioned, key indices are introduced to monitor the estimated level of risk and the level of knowledge on the structural condition. The proposed risk assessment methodology has thus been designed to allow these indices to be updated easily after any diagnosis activity or intervention is performed.

As summarised in Fig. 1, the proposed methodology involves a standardised initial expert appraisal (SIEA) that needs to be completed by the professional responsible for structural risk assessment after an initial desk study and inspection have been carried out.

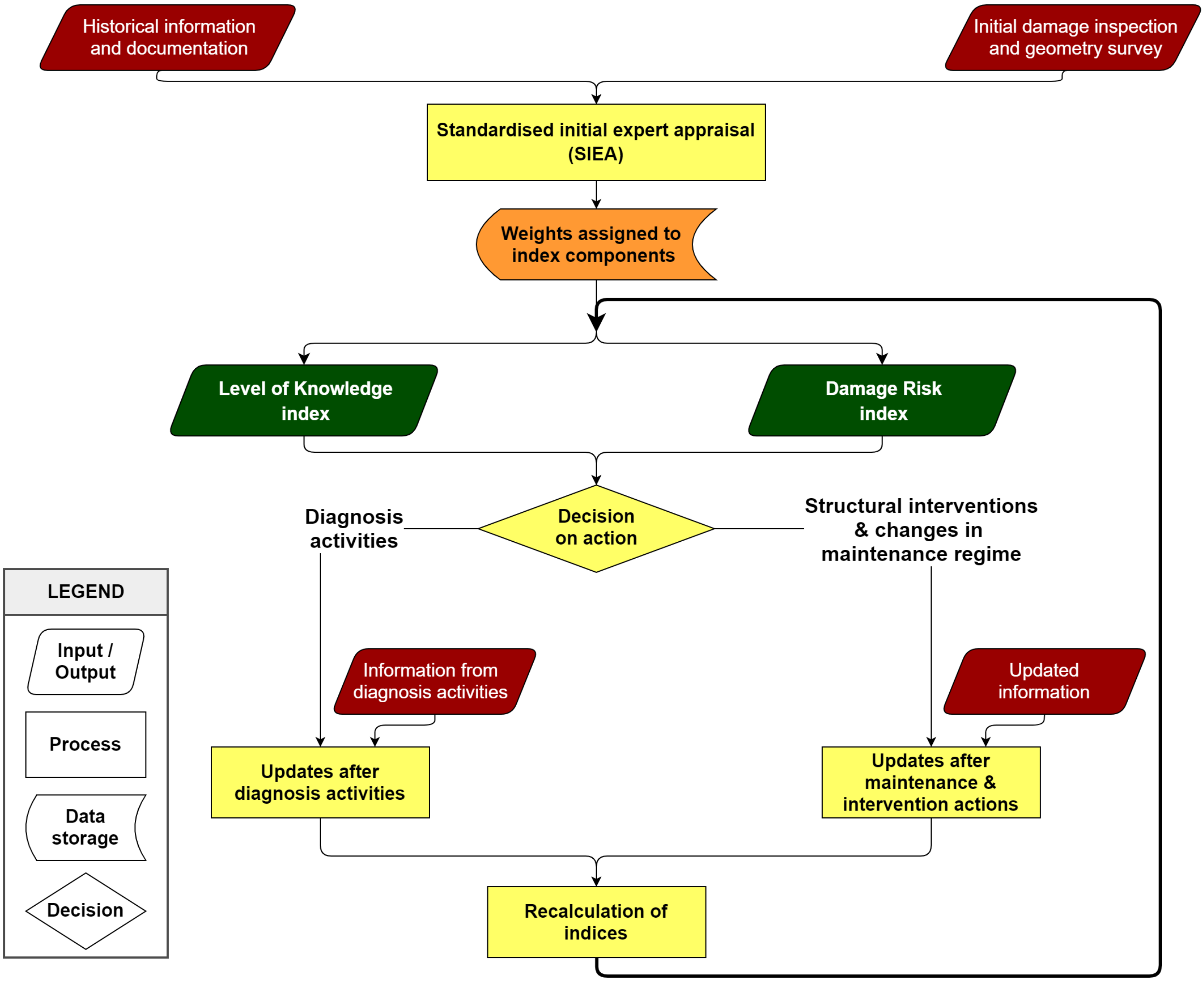


Figure 1: Proposed general risk assessment methodology.

Before the SIEA, all relevant available documents should be gathered and analysed to produce reliable information about the structural history of the building. In addition, an initial inspection should be carried out to identify the most important signs of decay and damage, to formulate initial hypotheses on potential active deterioration phenomena, and to decide whether there are immediate risks requiring urgent action. This inspection can also include measurements to obtain a general idea of key dimensions. The initial understanding of the structure provided by these activities can then be used to give an appropriate direction to subsequent investigations.

The SIEA has thus been designed in two parts. The first contains a standard set of questions requiring answers in the form of ratings that can be used to provide an initial understanding of the damage risk and the level of knowledge on the structural condition. The second part requires the expert to rank structural analysis goals and to rate the potential value of information that can be obtained from different research activities for assessing damage vulnerability. All rankings and ratings provided are then used to define weights among criteria and to compute initial values for two standard indices: the Level of Knowledge (LoK) index and the Damage Risk (DR) index. The actual components and structure of these two indices are described in detail in Sections 4 and 5.

Once the initial values of the indices are evaluated, the expert has to make a decision on the best course of action to safeguard the cultural and historical value of the structure as a whole. Possible decision alternatives usually include performing further diagnosis activities for a more complete and reliable assessment of vulnerability, performing structural interventions based on the current level of knowledge, or implementing an improved maintenance programme. As such, answers to standard questions have to be given or updated after each diagnosis activity or intervention is performed in order to update the LoK and DR index values accordingly. A brief description of all standard questions included as part of the proposed methodology is given in Section 3, while a detailed explanation of how to update index values after performing different types of activities is given in Section 6. Of course, following risk assessment, the decision may be that no action is required. If this is the case, the values of the LoK and DR indices remain unchanged until a re-evaluation is deemed necessary.

3. Standard questions for evaluating and updating indices

This section provides a brief overview of all standard questions that can be used to evaluate and update the LoK and DR indices. These questions can be broadly categorised as essential or optional. Answers to essential questions are required to compute initial values of the indices and therefore need to be provided during the standardised initial expert appraisal (SIEA). Answers to optional questions provide relevant information for risk assessment from various diagnosis activities. As such, specific relevant questions only need to be answered after a particular diagnosis activity has been performed. It is important to note that all questions have been arranged according to the logical order for which it would be most convenient for the user to answer them, and not according to the structure of the LoK and DR indices.

3.1. Essential questions

The individual questions that need to be answered during the two parts of the SIEA are not listed here but can be found in Appendix A, together with explanations of the possible range of answers.

3.1.1. Initial evaluation of level of knowledge and damage risk

The first part of the SIEA consists of 11 questions that require answers in the form of ratings. As previously mentioned, these are used to compute the initial values of the LoK and DR indices. Some of these questions consist of more than one part. Specifically, answers from the 4 parts of question 1 are used to establish the level of knowledge in terms of historical information and documentation. Questions 2 and 3 provide information on the level of knowledge in terms of geometry and damage mapping. Question 4 is related to the assessment of material quality from visual inspections and consists of two parts: the first informs the LoK index while the second informs the DR index. The remaining questions in the first part of the SIEA are all used in the computation of the DR index. Question 5 provides information on the level of exposure in terms of cultural value and potential loss. Questions 6 and 7 provide information on the damage vulnerability linked respectively to poor maintenance and to the need for urgent action. The latter has been included to allow the vulnerability component of the DR index to take into consideration situations for which the maintenance of the current structural condition can clearly not be guaranteed, even in the very short term, until immediate corrective action is undertaken. First and foremost, this includes situations in which (part of) a structural element is found to be in an evident precarious equilibrium state requiring immediate stabilisation.

As stated in Section 2, the SIEA needs to be performed after an initial desk study and inspection. Typically, this means that at least some information on the history, on visible damage, and on the geometry will be available at this stage. Although the vulnerability assessment that can be performed solely on the basis of this information is limited, there exist expert systems that can help to better understand the possible causes of visible damage [81, 83, 84], and MCDM indices that aim to characterise damage vulnerability or risk on the basis of this information alone [57–59]. In fact, the detailed interpretation and analysis of visible damages is usually a very important component of any explanatory report produced by an expert as the result of a structural diagnosis task. In most cases, such analyses prove most useful for characterising the vulnerability to slowly evolving progressive collapse mechanisms since characterising the vulnerability to catastrophic events requires a better understanding of probable event intensities. It is important that insights obtained as a result of this type of analysis be considered when making risk mitigation decisions. As such, question 8 has been included in the first part of the SIEA so that relevant outcomes from such analyses of historical information, geometry, and damage is considered in the assessment of vulnerability to progressive collapse mechanisms. In fact, the output from certain proposed simplified assessment methods such as [59] can be directly transformed to the scale of the rating that has to be provided as an answer to this question.

Questions 9 and 10 are related to earthquakes and other catastrophic events respectively. They both consist of two corresponding parts. The first part of each question deals with the hazard level and the second one with the vulnerability to these specific hazards. The reference peak ground acceleration with a 10% probability of being exceeded in 50 years is used to define the seismic hazard. In order to establish a suitable rating for the hazard level linked to other catastrophic events, the expert performing risk assessment should refer to appropriate intensity measures based on probable events in the specific geographic location of the structure. Several simplified approaches for a first-level assessment of seismic vulnerability have been developed whose implementation only require some basic knowledge of the structure's geometry, history, and visible damages [64, 67, 68]. The *Seismic Safety Index* proposed for the first evaluation level in the aforementioned Italian Guidelines [72, 73] can also be considered as such an approach. Within the proposed risk assessment methodology, results from the prior application of these simplified methods can be used to provide the required rating for the second part of question 9. Information about past performance to earthquakes and evidence on the structure in terms of damage can also be used to complement the result of some first-level evaluations and this should be considered by the expert when specifying this rating. If the vulnerability to other catastrophic events is deemed as being relevant for risk assessment (see Section 3.1.2), the same type of information and evidence should be taken into consideration for answering the second part of question 10. For some specific catastrophic events, results from other specifically developed first assessment methods can also be used to inform this rating. For instance, the wind-risk prioritisation index proposed for some types of cultural heritage assets [75] can be adapted to be used for evaluating the vulnerability of other masonry heritage typologies to strong wind events.

Finally, question 11 involves assessing the fire hazard. Although the evaluation of fire safety is in itself a complex task which can involve different detailed levels of study, the potential impact of a fire on the structural integrity of a masonry heritage structure is considered through a single hazard rating in the proposed risk assessment methodology. The performance based approach for evaluating the fire safety of historic buildings proposed in [87] can be used to adequately inform the score assigned to this criteria. Of course, this rating should be updated if any measures are taken to improve fire safety (through compartmentalization or by installing active fire suppression measures).

In total, if no urgent action is deemed necessary, 19 ratings have to be provided during the first part of the SIEA. Of these, 7 ratings are used to inform the LoK index, 7 are used to inform the vulnerability component of the DR index, 2 are used to inform the exposure component of the DR index, and 3 are used to inform the hazard component of the DR index. If urgent action is deemed necessary, an additional rating is required to score a vulnerability criteria linked to the potential extent of damage should the required urgent action not be undertaken.

3.1.2. Assessing the importance of different diagnosis activities

As previously mentioned, rankings and ratings provided in the second part of the SIEA are used to define the weights assigned to specific components of the LoK and DR indices. This allows the hierarchical structure of the two indices to be modified based on singular characteristics of different monuments. Since the two indices are used to describe the decision problem within the proposed risk assessment methodology, this weight-setting procedure enables meaningful insights to be drawn even if the methodology is applied to different structures with unique characteristics. The hierarchical structures of the two indices and the procedure used to establish weights from the provided ratings are described in greater detail in Sections 4 and 5.

This part of the SIEA consists of 8 questions (12 to 19), all of which are made up of several parts. The first and second parts of question 12 determine whether the vulnerability to earthquakes or other catastrophic events are explicitly considered in the assessment. If the decision is taken to include the vulnerability to these specific hazards, they will have to be assessed and ratings will have to be provided to define the possible contribution of different structural analysis and monitoring tools to the level of knowledge on these specific vulnerabilities. If the decision is taken to exclude a specific vulnerability, it will not be explicitly considered when evaluating the global damage vulnerability. However, it is worth noting that the hazard related to earthquakes and other catastrophic events will still be included in the global risk assessment. The third part of question 12 involves ranking the following 3 possible aims of structural analysis according to their importance for global damage vulnerability characterisation:

1. Structural analysis aimed at better understanding the vulnerability to progressive collapse.
2. Structural analysis aimed at better understanding the vulnerability to earthquakes.
3. Structural analysis aimed at better understanding the vulnerability to other catastrophic events.

The assigned ranks are then used to determine the relative importance that these 3 aims are given in the vulnerability component of the DR index. Naturally, if the vulnerability to earthquakes or to other catastrophic events has already been excluded from the analysis in the first two parts of question 12, only the remaining relevant aims need to be ranked. If both have already been excluded, only the vulnerability to progressive collapse is considered. The vulnerabilities to specific hazards are treated separately in the proposed assessment procedure mainly because they can differ significantly. For instance, a structure can prove to have adequate capacity to withstand its normal working loads while still being extremely vulnerable to suffering damage during an earthquake. In addition, this separation is also implemented because the suitability of different structural analysis and monitoring tools for diagnosis can change depending on the specific vulnerability under evaluation.

Once a decision has been made on including the vulnerability to specific hazards in the risk assessment, ratings have to be provided to evaluate the suitability of specific diagnosis activities. The information from several different types of activities can be included in the proposed risk assessment procedure. Diagnosis activities are grouped together according to the type of information they can provide, ratings are used to assign weights among activities within a group based on their possible contribution to the level of knowledge on damage vulnerability. Specifically, 5 groups of activities have been identified:

- Structural analysis and SHM
- Activities involving the evaluation of specific mechanical, physical, or chemical properties of materials
- Geometry and damage surveys
- Activities to characterise material quality and variability
- Activities to evaluate actual loading and boundary conditions in-situ

Although the choice of grouping structural analysis and SHM together might appear counter-intuitive as they are often executed separately, it stems mainly from the fact that these two types of activities can be combined in many different ways to provide complementary information on the capacity and response of a monument to specific structural actions. As such, they were grouped together to allow the expert performing risk assessment to adjust the relative importance of information from specific structural analysis and SHM activities depending on the particular characteristics of the structure. Question 13 thus involves rating different structural analysis and SHM activities based on the extent to which it can help assess the structure's vulnerability to progressive collapse. Activities that need to be rated include: evaluating the loads supported by different members (load report), graphic statics and limit analysis, numerical modelling, dynamic SHM, and static SHM. Each activity can be rated as 0, 1 or 2. Activities that are rated as 0 will not be considered in the risk assessment. This choice can be made if the information that an activity can provide is deemed irrelevant or if the cost of performing an activity is already known to be too high for a given project. Conversely, activities that are deemed essential or that can contribute significantly to the vulnerability assessment should be rated as 2. Finally, activities that can only complement the vulnerability assessment should be rated as 1. For question 13, if limit analysis procedures or numerical modelling are given a rating which is greater than 0, the rating attributed to the load report is automatically fixed at 1 because evaluating the loading scenario is a necessary preliminary step before performing limit analysis or numerical modelling. If the vulnerability to earthquakes and other catastrophic events are included in the risk assessment, the value of different structural analysis and SHM activities for assessing these specific vulnerabilities also needs to be evaluated. This is achieved by rating activities listed in questions 14 and 15. With the exception of the load report, the same activities listed in question 13 are included in these two questions. The same rating scale is also used.

In fact, the same scale is used to rate the different activities in other groups. Tests for estimating material properties need to be rated in question 16, possible geometry and damage mapping activities need to be rated in question 17, and activities linked to the characterisation of material quality and variability need to be rated in question 18. Finally, ratings need to be assigned in question 19 for different in-situ activities that can be used to evaluate actual loading and boundary conditions.

In total, 39 ratings have to be given in the second part of the SIEA to assign the weights that specific criteria related to different diagnosis activities have in the LoK and DR indices.

3.2. Optional questions

Once the essential questions from the standardised initial expert appraisal (SIEA) have been completed, the LoK and DR indices need to be updated every time an additional diagnosis activity is performed. To achieve this, the proposed risk assessment framework includes specific questions related to many possible diagnosis activities. Of course, the answers to these questions only need to be completed or updated after relevant activities have been performed. The answers provided are then used to re-evaluate the LoK and DR index values as described in Sections 4 and 5.

The optional questions are organised according to the 5 identified activity groups listed in Section 3.1.2. These questions are not listed here but can be found in Appendices B to F, together with explanations of the possible range of answers. In general, each question relates to a specific diagnosis activity and consists of several parts. In most cases, each question specifically consists of at least one part used for evaluating the LoK index, and at least another part used for evaluating the DR index.

However, optional questions related to additional geometry and damage surveys only consist of a single part used to update the LoK index based on the effectiveness of the activities in addressing the lack of knowledge on geometry and damage. Naturally, the global ratings given during the first part of the SIEA on the level of knowledge on geometry (question 2) and existing damage (question 3) need to be updated after any of the geometry and damage mapping activities are carried out. Relevant vulnerability ratings provided in the first part of the SIEA can also be updated if the new information on geometry and damage changes the initial perception of vulnerability.

It is also worth mentioning that the proposed framework includes distinct optional questions for structural analysis and SHM activities aimed at better understanding the vulnerability to progressive collapse mechanisms, to earthquakes, and to other catastrophic events. In addition, for the case of static SHM, both the LoK and DR indices can be periodically updated after an initial configuration by taking advantage of processed results from the methodology described in [35].

In total, the proposed framework includes 85 possible ratings that can be used to update the MCDM indices after specific diagnosis activities have been performed. Of those, 46 are used to score criteria in the LoK index and 39 are used to score criteria from the vulnerability component of the DR index.

4. Level of knowledge index

The risk assessment methodology proposed as part of this research involves the computation of a distinct Level of Knowledge (LoK) index. This is in contrast to the methods proposed in the Italian and PERPETUATE guidelines for seismic safety assessment, which account for the level of knowledge through different confidence factors applied to material properties or other parameters in their respective verification procedures [72, 74]. This choice was made to allow for the explicit consideration of the depth of study when making risk mitigation decisions through a systemically structured key performance indicator, the LoK index.

All answers to questions related to the level of knowledge are provided in the form of a rating ranging from 0 to 5, with 0 representing no information and 5 representing the highest possible level of knowledge. Each rating can be provided as any rational number within this range and will eventually be combined into a single LoK index to facilitate the decision-making process. The questions have been designed so that ratings represent the comprehensiveness of the different types of research activities performed. Generally, as more and more relevant in-depth investigations are carried out, the uncertainty associated to vulnerability assessment should decrease. As such, the index is intended to inform decision makers on the general level of uncertainty related to the vulnerability assessment, with a higher level of knowledge indicating less uncertainty. Based on applications to case studies, it can be considered that final LoK index values ranging from 0 to 1.5 represent a low level of knowledge while values between 3 to 5 represent a high level of knowledge. Therefore, index values from 1.5 to 3 suggest a moderate level of knowledge on damage vulnerability.

4.1. Value functions

At this stage, it is relevant to highlight a particular feature of the process behind safety evaluation. When no information is available on a structure, significant improvements can often be made to the understanding of vulnerability through the acquisition of a few key pieces of information and using simplified analysis methods. However, as the general level of knowledge increases, further reducing the uncertainty associated to the vulnerability assessment typically requires more and more effort. In other words, as our understanding of a structure improves, identifying damage causes or quantifying capacity with even greater accuracy usually requires employing even more sophisticated methods and acquiring even more data. This learning effect can be considered in the computation of the LoK index value by transforming the original ratings to a suitable score using an ascending concave value function (see Fig. 2). Effectively, due to the decreasing slope of such a function, a small increase from a low rating causes a greater increase in the transformed score when compared to the same increment added to a higher rating.

As described in Section 5, similar value functions are also employed in the computation of the DR index to convert answers from specific questions into homogenised scores. As such, a single expression that depends on a few parameters is defined for all value functions employed within the risk assessment framework. The parameters can be modified so that the curvature of the function can be adjusted to best represent the relationship between the original units of the answer and the homogenised score used for computing the final index value. The general value function employed in this research is shown in Eq. (1). It has been adapted from the one proposed as part of a method known as MIVES [88, 89], which was initially developed for sustainability assessment.

$$S_i(X_i) = K_i \cdot \left[1 - \exp\left(-m_i\left(\frac{|X_i - X^*|}{n_i}\right)^{A_i}\right)\right] + S_{min} \tag{1}$$

$$K_i = \frac{S_{max} - S_{min}}{1 - \exp\left(-m_i\left(\frac{|X_{max} - X_{min}|}{n_i}\right)^{A_i}\right)} \tag{2}$$

Where S_i represents each homogenised score that will be combined to compute the LoK index value and X_i refers to each rating provided to update the LoK index. K_i is a factor that can be used to scale the range of the resulting index score. It is computed as shown in Eq. (2). In this case, the LoK index has a range which can vary from 0 (S_{min}) representing no knowledge at all to 5 (S_{max}) representing very comprehensive knowledge. X_{max} and X_{min} are the maximum and minimum possible rating values, which are also 5 and 0 for all LoK questions. X^* can be either X_{min} or X_{max} depending on if the answer is a maximising positive defined criteria or not. In the case of the LoK index, because all questions have been set so that a higher rating represents a higher level of knowledge, $X^* = X_{min}$. The constants m_i and n_i can be used to modify the geometry of the value function and they have been set at 1 and 20 for the function used to transform all answers related to the level of knowledge. Finally, A_i is a shape factor that defines approximately whether the curve is concave ($A_i < 1$), close to a straight line ($A_i \approx 1$), or whether it is convex or S-shaped ($A_i > 1$). In the case of the LoK index, the expert completing the SIEA can choose between five different concavity settings to best reflect the learning curve associated with the particular structure of interest. If the LoK concavity is set to 0, the ratings provided as answers to questions are directly combined to compute the index. Otherwise, the four other settings included in the framework are shown in Fig. 2. They correspond to substituting the values of 0.95, 0.85, 0.75 and 0.65 for A_i in Eq. (1).

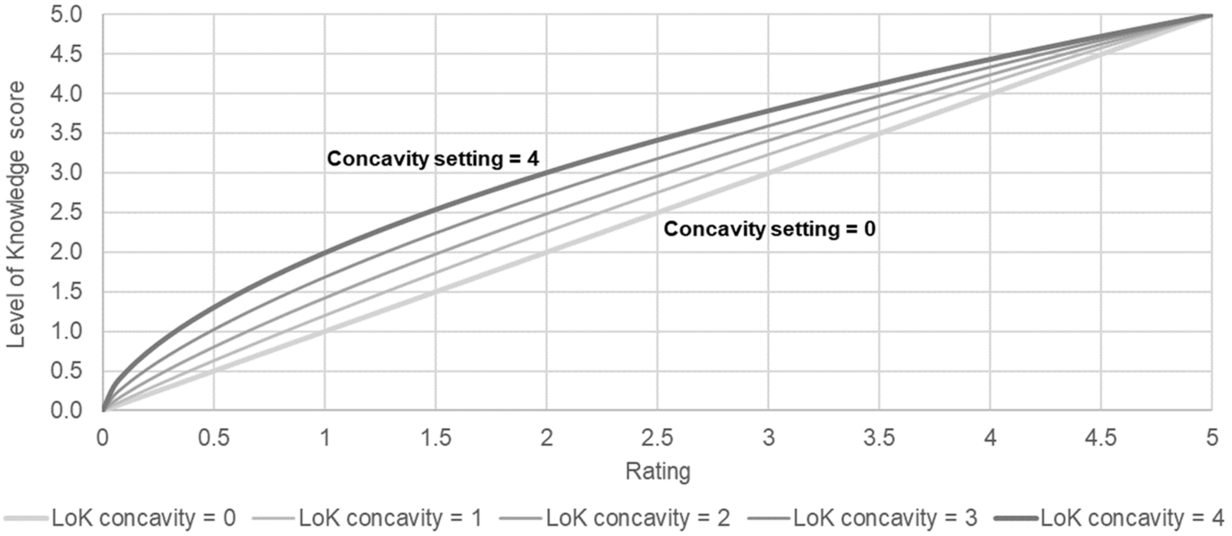


Figure 2: Possible settings to adjust the transformation of ratings given as answers to questions into scores used for computing the value of the LoK index.

As shown in Figs. 3 and 4, most of the branches forming the hierarchical structure of the LoK index end on a criteria which depends on the rating from a single question. In such cases, the value function can simply be applied directly to the rating before proceeding with the computation of the index. However, when it comes to the experimental characterisation of specific material properties, the value used to represent the comprehensiveness of relevant investigations is taken as the mean of two ratings (see Fig. 3): one related to the confidence level of estimates and another to the coverage area of the investigation. Similarly, in the case of static or dynamic SHM, the value used to represent the comprehensiveness of investigations is also taken as the mean of two ratings: one related to coverage area and another to monitoring duration (see Fig. 4). In both cases, the value function is applied on the mean of the two relevant ratings. In the case of static SHM, the monitoring duration is taken directly as the number of years. This is then converted to a suitable level of knowledge rating using an ascending concave value function designed so that the rating varies between 0 to 5 as the monitoring duration increases from 0 to 15 years. In particular, the transition from a low to a moderate level of knowledge (corresponding approximately to a rating of 1.5) occurs after 2.4 years while the transition from a moderate to a high one (rating of 3) occurs after 6.6 years. The value function providing such a transformation can be represented by Eq. (1) with $X^* = X_{min} = 0$, $X_{max} = 15$, $m_i = 2$, $n_i = 100$ and $A_i = 0.75$.

4.2. LoK index structure and criteria

Once the answers to the standard questions are converted to homogenised scores that can reflect the level of knowledge on the structural condition, they are combined according to the hierarchical structure shown in Figs. 3 and 4 using simple additive weighting (SAW). Relevant diagnosis activities are grouped according to the type of information they can provide for evaluating the structural condition of a masonry heritage structure. As shown, the relative weights among these groups at the first level of the hierarchical structure are constant. This is because a strong assumption behind the LoK index is that the relative importance among these groups remains unchanged in terms of the information they can provide for global vulnerability assessment. For instance, structural analysis is definitely considered as being of considerable importance since it is the only activity able to provide direct quantitative estimates of safety levels. It is able to achieve this by evaluating both demand and capacity through the use of mathematical models.

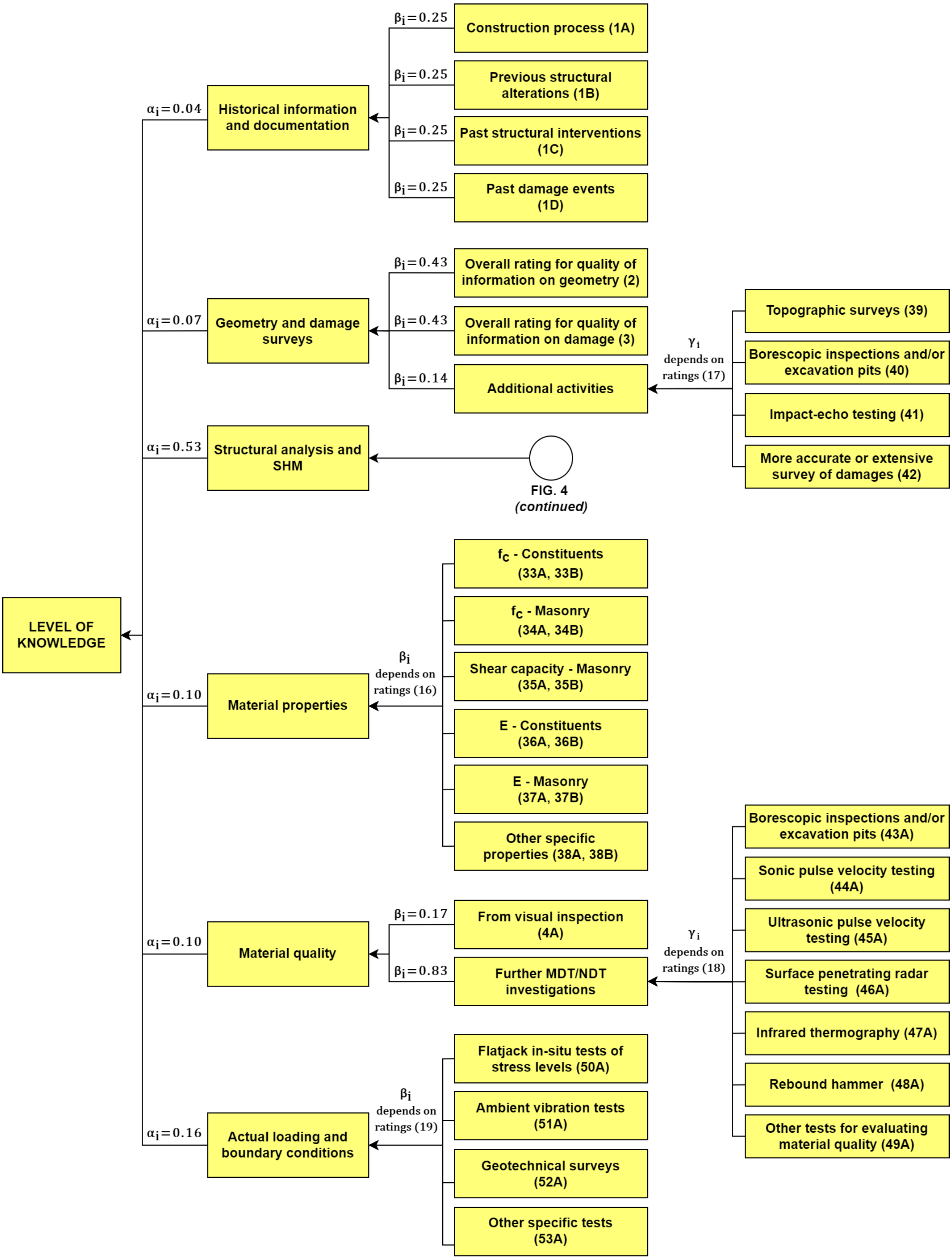


Figure 3: Criteria tree for the index representing the general level of knowledge on damage vulnerability. The relevant question references are shown in brackets at the end of each branch. Parameters α_i, β_i, and γ_i refer to relevant weights that need to be applied to criteria at the first, second, and third hierarchical level respectively.

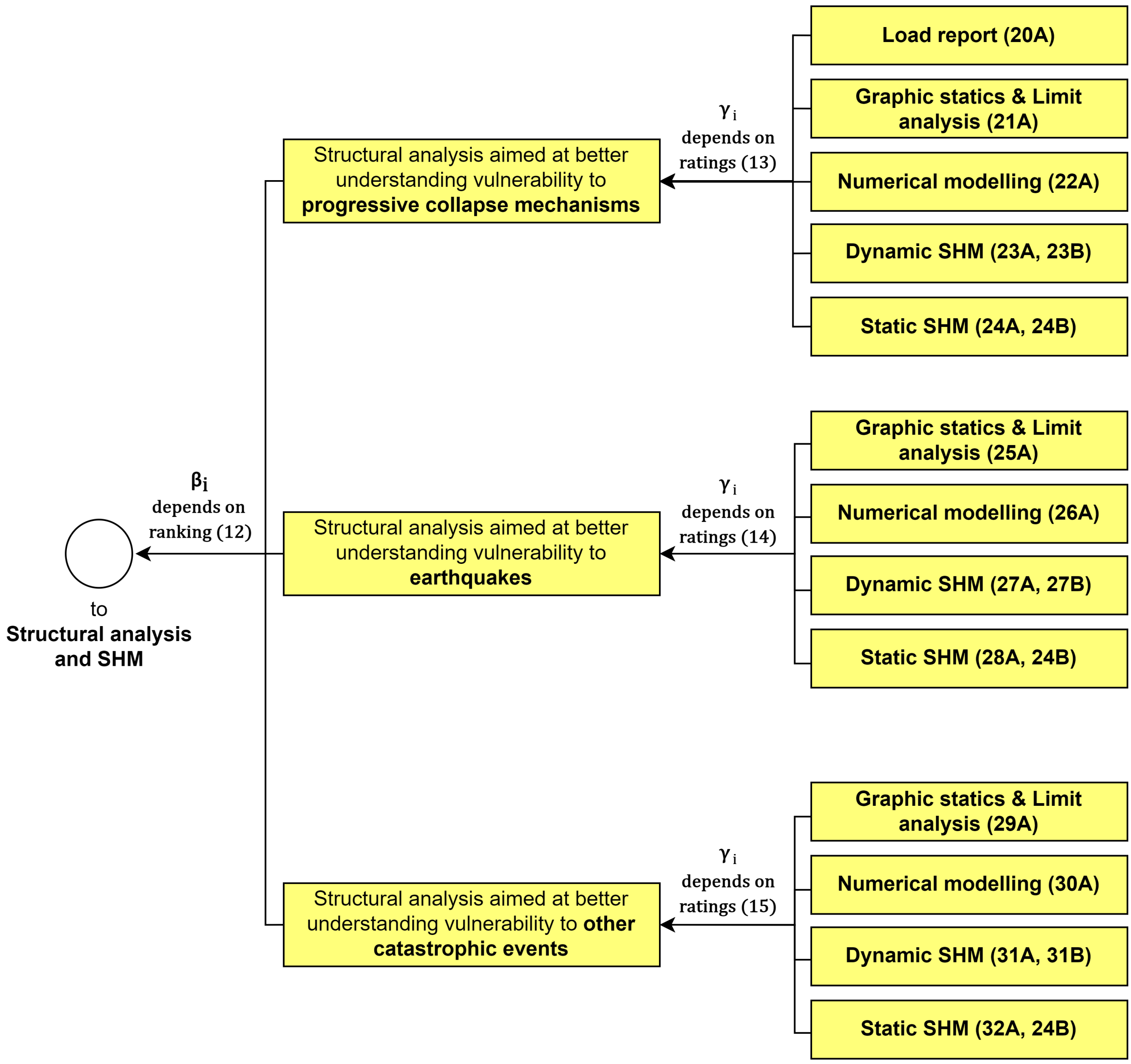


Figure 4: Criteria tree for the level of knowledge sub-indicator related to information from structural analysis and SHM. The relevant question references are shown in brackets at the end of each branch. Parameters β_i and γ_i refer to relevant weights that need to be applied respectively to criteria at the second and third hierarchical level of the global level of knowledge index.

As previously mentioned in Section 3.1.2, SHM activities are grouped together with structural analysis because of the diverse ways in which they can be combined to provide information on damage causes, as well as on the structural response and capacity. The fact that they are grouped together allows the expert responsible for risk assessment to rate the importance of structural analysis and SHM activities relative to each other based on foreseeable combined applications that are appropriate for the unique characteristics of a monument. As shown in Fig. 3, the remaining identified activity groups include the analysis of historical information and available documentation, activities related to capturing the actual geometry and damage, evaluating specific material properties, characterising material quality and variability, and performing in-situ tests to determine actual loading and boundary conditions.

For the computation of the global LoK index, appropriate relevance factors are needed to represent the relative importance of information that can potentially be derived from each group of activities. In order to reduce the subjectivity involved in this task, a popular procedure in the realm of decision analysis known as the analytical hierarchy process (AHP) [90, 91] was employed. This procedure allows an analyst to conduct a rational and consistent assessment of weights by first establishing pairwise comparisons among parameters under consideration at the same hierarchy level. A well-defined fundamental scale ranging from 1 to 9 must be used to evaluate the intensity of the importance of each parameter over another. According to the scale, 1 is used if two parameters are of equal importance whereas 9 is used to define the extreme importance of one parameter over another. The AHP then allows weights to be obtained for each parameter based on solving an eigenvalue problem after collecting the individual comparison scores into a matrix. The pairwise comparison matrix constructed for evaluating the weights among different activity groups is shown in Table 1, together with the resulting priority vector containing the relative weights attributed to each group. An additional benefit of using the AHP for determining weights is that a procedure is defined for verifying the consistency of the pairwise judgements provided. The verification first involves computing a consistency index, which is a function of the largest eigenvalue calculated as a solution of the AHP and the rank of the judgement matrix. Once this index is computed, a ratio is found by dividing it by a random consistency index. The latter is the average consistency index of a large number of randomly generated reciprocal matrices. If the final consistency ratio is smaller than 10%, the weights can be considered as being logically sound [90]. It was ensured that this consistency condition was satisfied for all AHP comparisons used as part of this research.

Table 1: Pairwise comparison matrix and resulting priority vector containing the weights assigned to the importance of information from different activity groups for the global level of knowledge.

	A	B	C	D	E	F	**Priority Vector**
A. Historical info. & docs.	1	1/3	1/7	1/4	1/4	1/4	**4%**
B. Geometry & damage	3	1	1/6	1/2	1/2	1/3	**7%**
C. Structural analysis & SHM	7	6	1	6	6	6	**53%**
D. Material properties	4	2	1/6	1	1	1/2	**10%**
E. Material quality	4	2	1/6	1	1	1/2	**10%**
F. In-situ conditions	4	3	1/6	2	3	1	**16%**

As shown in Table 1 and Fig. 3, structural analysis and SHM are very important when compared to any other activity group. This is partly due to the ability of some structural analysis methods to provide quantitative estimates of safety levels and also partly due to the large breadth and depth of information that such methods can provide for vulnerability assessment. As a result, following the application of the AHP, more than half of the contribution to the LoK index relies on information from structural analysis and SHM activities.

The second most influential group for the computation of the LoK index involves in-situ tests to evaluate actual loading and boundary conditions. Such tests are often specifically designed or adapted to investigate specific unknown parameters that are deemed to be of interest for vulnerability assessment. In addition, they are often the only possible way of obtaining key information on real conditions that can prove to be vital for validating models used to better understand the structural condition and associated safety levels. This explains why this activity group is given moderate importance over all other groups except structural analysis and SHM.

The next two most influential activity groups are related to the estimation of material properties and to the characterisation of material quality and variability. Both groups of activities end up contributing 10% to the LoK index following the AHP. In fact, these two activity groups can provide complementary information as both activity types posses characteristics suitable to address some weaknesses of the other. Tests to estimate material properties, particularly mechanical parameters, can provide key information for structural analysis. However, it is often unfeasible to test enough specimens so that the sample provides a good representation of the variability of material properties in different parts of a structure. In contrast, although several NDT methods used for characterising material quality can cover large areas of the structure, they are usually limited in terms of the information they can provide on the strength and deformation properties of the material. Nevertheless, performing activities categorised in these two groups are often the only way of obtaining information on materials that can be indispensable for an accurate vulnerability assessment.

Following the activities linked to material characterisation, geometry and damage surveys are the next biggest contributors to the LoK index. It is undeniable that accurate representations of a structure's geometry and damage are key to an accurate vulnerability assessment. Reliable information on these aspects of a heritage structure are not only required for many different types of analyses and for validating models, but it also forms much of the basis for the development of initial hypotheses on possible causes of damage and for early decisions on the most suitable activities for further investigations. However, as a greater level of sophistication is applied to improve vulnerability assessment, information on geometry and visible damage often becomes mostly useful for planning tests, to accurately represent real conditions in sophisticated analyses, and for validating results. In other words, when the level of knowledge on damage vulnerability is moderate or high, significant further improvements normally cannot be attained only by performing more geometry and damage surveys. This explains why the relative importance assigned to this group of activities is relatively low.

Finally, information from the historical survey has been assigned the lowest weight in the first level of the hierarchical structure of the LoK index. This choice does not absolutely mean that the historical survey is a superfluous activity that may be omitted in the studies of conservation of the built heritage, as it definitely constitutes the essential preliminary stage of the scientific method [1]. However, the choice of a lower weight is partly due to the limited reliability of historical sources. As a result, information needs to be critically assessed and assumptions often need to be made when interpreting it [1]. Furthermore, useful documents have often been prepared for purposes other than structural engineering, meaning that relevant technical information might be missing or incorrect. In addition, much like information on the structure's geometry, information acquired through a historical survey often cannot contribute directly to improving an already high level of knowledge on damage vulnerability.

As shown in Figs. 3 and 4, many of the weights among criteria at subsequent levels depend on the ratings provided during the second part of the SIEA (see Section 3.1.2). Exceptions to this are criteria related to historical information and documentation, to the actual geometry and visible damage, and to the material quality. This is because some of the information contributing to the weighted score linked to these activity groups are taken from answers provided during the first part of the SIEA. In fact, for the score representing the level of knowledge in terms of historical information, all relevant ratings are provided during the SIEA. Of course, these can be modified if new information becomes available, but this does not affect the hierarchical structure of the index. As shown in Fig. 3, four scores are used for computing the combined score linked to historical information. These are related to the comprehensiveness and quality of information available on the construction process, on past damage events and on previous structural alterations and interventions. Because information from any of these aspects can be equally pertinent for vulnerability assessment, equal weights are assigned to each in the computation of the LoK index.

With respect to the weighted score linked to the level of knowledge on geometry and visible damage, it is influenced mostly by the global ratings provided by the expert responsible for geometry and damage surveys. These ratings are initially provided during the first part of the SIEA (questions 2 and 3) but have to be updated after carrying out any activities involving the acquisition of information on geometry or damage. Clearly, if such activities are deemed to be relevant during the second part of the SIEA, it reveals an identified lack of knowledge. To account for activities carried out to address this gap, the score representing the level of knowledge on geometry and damage depends on a third criteria derived as a weighted total of the scores representing the comprehensiveness of information from specific additional activities (see Fig. 3). Specifically, both of the global ratings on geometry and damage contribute 43% to the final weighted score linked to this activity group, while the remaining 14% is based on additional activities that are deemed relevant. These weights correspond to the outcome of applying the AHP after attributing equal importance to the two global ratings and giving both moderate importance over the information from additional activities. If all such activities are deemed as being irrelevant during the second part of the SIEA, the score related to geometry and damage depends only on the two global ratings with equal importance assigned to each.

The weighted score representing the level of knowledge on material quality depends on two criteria. The first reflects how well the material quality could be evaluated from visual inspections and the second represents the comprehensiveness of further investigations. Because results from MDT and NDT procedures for evaluating material quality can be much more informative when compared to the limited evaluation that can be made from visual inspections, 83% of the level of knowledge score for material quality relies on the comprehensiveness of MDT and NDT investigations while only 17% is attributed to the visual inspection conditions. This corresponds to a strong importance attributed to further investigations in an AHP context. As is the case for additional activities related to geometry and damage, if all further investigations on material quality are deemed to be irrelevant during the SIEA, the level of knowledge on material quality depends only on the conditions of visual inspections.

For all remaining activity groups, the relative weights among relevant criteria at subsequent levels of the hierarchical structure depend only on rankings and ratings provided during the second part of the SIEA. For activity groups related to the estimation of material properties and the evaluation of in-situ conditions, the score for each group is directly based on the weighted sum of scores representing the level of knowledge for individual activities (see Fig. 3). As mentioned in Section 3.1.2, the importance of the information that each individual activity can provide for global vulnerability assessment is rated as either 0, 1 or 2 depending on its possible contribution. The relative weight attributed to activities rated as 0 is set to 0, meaning that information from the activity is no longer taken into consideration for risk assessment. The weights of remaining activities connected to a single parent criteria are then simply computed from the ratings provided as shown in Eq. (3).

$$\gamma_i = \frac{r_j}{\sum\limits_{j=1}^{n} r_j} \tag{3}$$

Where γ_i refers to the weight attributed to the score related to the individual activity i when computing the score of the parent criteria connected to n activities. On the other hand, r_i refers to the rating attributed to the importance of information from activity i during the SIEA (0, 1 or 2).

It should be noted that if the ratings of all individual activities connected to a single parent criteria are set to 0, the weight attributed to their parent criteria is also set to 0. This eliminated weight is then redistributed proportionally among remaining criteria connected to the same branch at the corresponding level.

As shown in Fig. 4, the hierarchical structure leading to the level of knowledge score for structural analysis and SHM has been designed to account for the fact that these activities can be planned for investigating the vulnerability to specific hazards. As described in Section 3.1.2, the weights attributed to each of the three possible aims (understanding the vulnerability to progressive collapse, earthquakes, or other catastrophes) depend on how they are ranked in the third part of question 12 during the SIEA. The specific aim ranked first is given a weight of 72% while the one ranked second is given a weight of 21%. The aim deemed as being least important is therefore attributed a weight of 8%. These were derived using the AHP from the pairwise comparison matrix shown in Table 2. The weights of the individual structural analysis and SHM activities connected to each specific aim are then computed using Eq. (3) from the ratings provided in the SIEA.

Table 2: Pairwise comparison matrix and resulting priority vector containing the weights reflecting the importance assigned to different aims of structural analysis and SHM (1: understanding the vulnerability to progressive collapse, 2: to earthquakes, and 3: to other catastrophes) based on how they were ranked.

Rank	1	2	3	**Priority Vector**
1	1	4	8	**71.7%**
2	1/4	1	3	**20.5%**
3	1/8	1/3	1	**7.8%**

4.3. Computation of the LoK index

Once all of the weights have been determined, the final LoK index value can then simply be computed using equation Eq. (4).

$$LoK\,index = \sum_{i=1}^{N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot S_{_{LoK,i}} \tag{4}$$

Where $S_{_{LoK,i}}$ refers to the score of a particular criteria at the end of one of the branches of the hierarchical structure shown in Fig. 3. The parameters α_i, β_i and γ_i refer to the weights that need to be applied at every level. For their assessment, see Figs. 3 and 4, Table 1, and Eq. 3. Of course, if a criteria is found at the end of a branch ending after the second level, γ_i should be considered as 1 (see Fig. 3). N refers to the number of individual criteria that are ultimately considered for the computation of the index. This number can change depending on how many activities are deemed as being irrelevant during the SIEA. If information from all possible activities are considered, $N = 41$.

The value of the LoK index should initially be computed after the SIEA. Following this, every time a diagnosis activity or intervention is performed, the appropriate ratings should be modified and the LoK index should be computed again (see Fig. 1). In this way, the LoK index can help inform decision makers on the uncertainty associated to vulnerability assessment within a dynamic process following the preventive conservation approach.

5. Damage risk index

As previously mentioned, the risk of interest for this research is that of a masonry heritage structure suffering from structural damage. Naturally, the most important requirement for a meaningful assessment of this risk is an appropriate diagnosis of the structural condition leading to an accurate evaluation of vulnerability. Nevertheless, as stated in the introduction, when deciding the best course of action to preserve such structures, experts have to consider hazard and exposure according to agreed-upon definitions in the context of disaster risk [79]. The final damage risk is therefore defined as being a function of vulnerability, hazard, and exposure, as shown in Fig. 5.

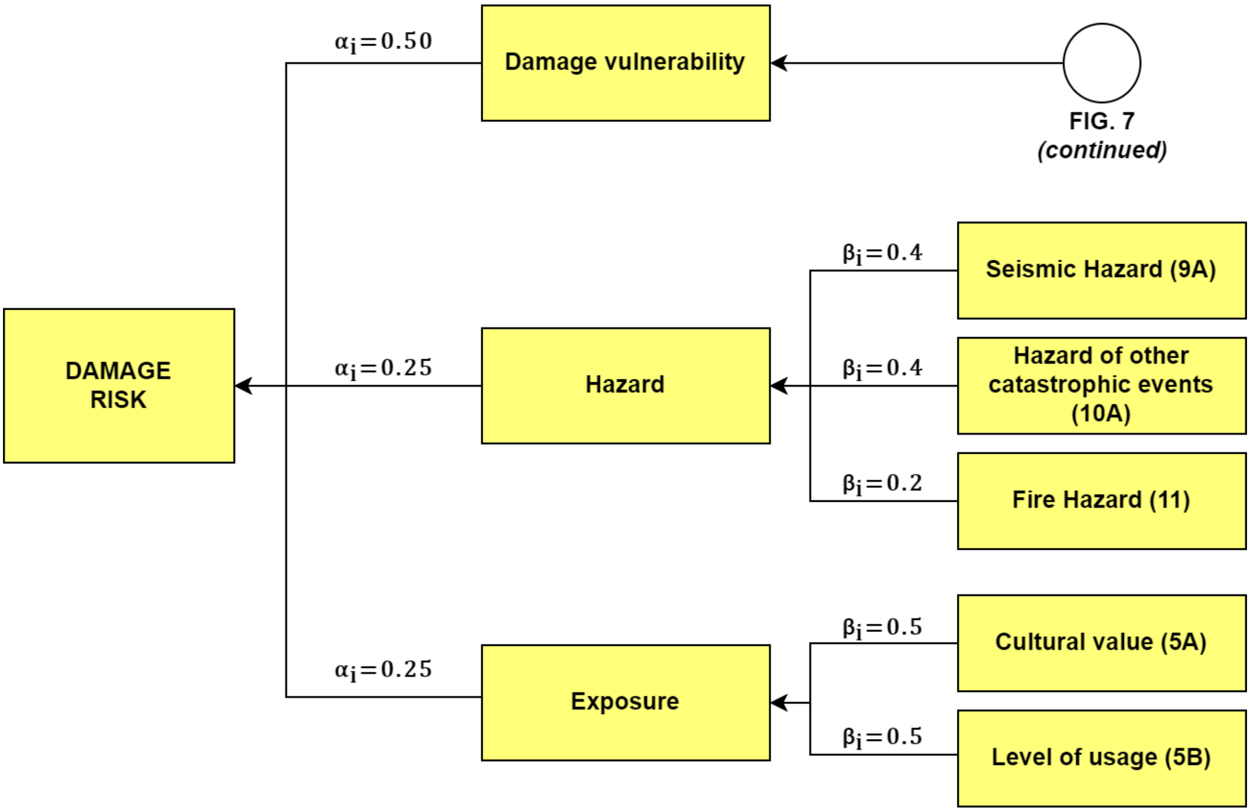


Figure 5: Criteria tree for the damage risk index. The relevant question references are shown in brackets at the end of each branch. Parameters α_i and β_i refer to relevant weights that need to be applied to criteria at the first and second hierarchical level respectively.

The damage risk (DR) index can vary from 1 representing the lowest possible risk level to 5 representing the highest. This means that all the criteria used to define it also need to be homogenised to this scale. Unlike the LoK index, the DR index can never be 0. This condition is set to facilitate the interpretation of index values for decision-making and to reflect the fact that there will never be a situation with absolutely no risk in the case of unique heritage structures.

Although the vulnerability component is analysed thoroughly as part of this research, the hazard and exposure components rely on recurrent criteria that are normally considered when making recommendations for mitigating the risk of structural damage. As such, they serve mainly to amplify or contract the resulting vulnerability score based on hazard and exposure conditions. It can therefore often be useful when making decisions to also directly examine the vulnerability component as a damage vulnerability (DV) index in its own right.

Despite the simplified approach employed to estimate the actual hazard and exposure level, they play a key role in defining the possible mitigation measures that can be employed. As such, they contribute 25% each to the final value of the DR index, while the value of the DV index determines the remaining 50%. In an AHP context, this is equivalent to giving damage vulnerability a slight importance over hazard and exposure while giving them equal importance amongst themselves.

All the information required to compute the scores related to hazard and exposure are provided during the first part of the SIEA. The final score linked to exposure depends on two ratings related to the cultural value and the potential loss based on the level of usage. In this case, the range of each possible rating has been designed so that no transformation is needed before combining them using additive weighting. As shown in Fig. 5, equal importance is assigned to the two ratings. The final hazard score depends on three criteria related to the intensity and probability of occurrence of fires, of earthquakes, and of other catastrophic events. With respect to the seismic hazard, the only information that needs to be supplied during the SIEA is the reference peak ground acceleration (PGA) with a 10% probability of being exceeded in 50 years. Very good estimates of this value for any region in the world can easily be obtained using an online interactive map [92]. The value function shown in Fig. 6(d) is then used to transform the supplied acceleration value to a hazard score ranging from 1 to 5. The function can be defined using Eq. (1) with the parameters shown in Table 3, and has been calibrated to be in good agreement with the hazard levels shown in [93]. As shown, the function transforms any PGA from 0.2 m/s^2 to 4 m/s^2 into a hazard score ranging from 1 to 5. It is implemented as a conditional formula so that any PGA below 0.2 m/s^2 is attributed a score of 1 while one greater than 4 m/s^2 is scored as 5. For the remaining two hazard components, their scores are taken directly as the ratings provided during the SIEA.

5.1. Damage vulnerability index

In addition to providing information on the hazard and exposure level, answers to questions from the first part of the SIEA also provide pertinent information for initial damage vulnerability assessment. These include ratings related to material quality, to the level of maintenance, to the need for urgent action, and to initial evaluations of the vulnerability to specific hazards. As mentioned in Section 3.2, a number of optional questions can also be answered to update the DV index based on the outcome of specific diagnosis activities.

5.1.1. DV index structure and criteria

Because it is much more intuitive to grade material quality on an ascending scale, the rating provided during the SIEA on this aspect (question 4B) can vary from 1 to 5 to reflect increasing levels of material quality and homogeneity. Naturally, this needs to be converted to a suitable homogenous vulnerability score before it can be considered in the DV index. This is achieved using the descending value function shown in Fig. 6(a), defined by substituting the parameters shown in Table 3 into Eq. (1). After inspecting and evaluating material quality, it can be very difficult to draw meaningful conclusions on the vulnerability of the structure if the material is deemed to be of moderate or moderately high quality. However, identifying clear signs of poor material quality and degradation has definitive implications for vulnerability, and this should be reflected with a high vulnerability score attributed to this criteria. This effect is accounted for through the choice of a convex shape for the descending value function related to this criteria as shown in Fig. 6(a).

Within the proposed framework, material quality is also graded according to an ascending scale after further MDT or NDT investigations have been carried out (questions in Appendix E). As such, the same value function is also applied to relevant material quality ratings after further investigations following the SIEA. In fact, it can be said that such an effect also holds true when evaluating the state of maintenance, whereby very poor conditions have a more pronounced effect on vulnerability. Within the proposed risk assessment methodology, two ratings have to be provided during the SIEA on the state of maintenance. The first rating is intended to represent the actual maintenance condition whereas the second one is meant to indicate the suitability of the current maintenance plan to address relevant pathologies. The final maintenance rating is then taken as the mean of these two. As is the case for the material quality rating, a convex descending value function is also employed to transform this rating into a vulnerability score. However, as shown in Fig. 6 and Table 3, different parameters are proposed for this criteria so that the curvature is better suited to the range of the maintenance condition rating.

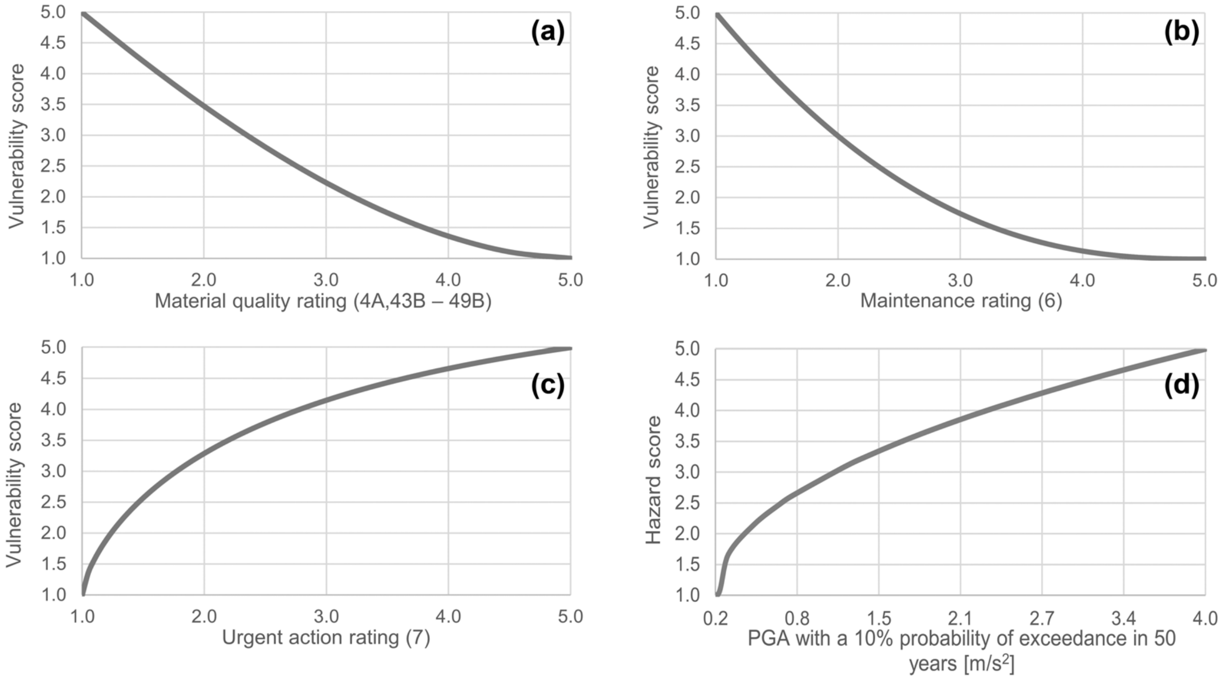


Figure 6: Value functions converting answers given in the first part of the SIEA to relevant homogenised scores to be combined in the DR index. The functions shown apply to material quality ratings (a), the maintenance rating (b), the urgent action rating (c), and the measure of seismic hazard (d).

Table 3: Parameters used in Eq. (1) to derive value functions for specific answers provided in the first part of the SIEA.

	X^*	X_{min}	X_{max}	m_i	n_i	A_i
Material quality (4A, 43B-49B)	X_{max}	1	5	1	10	1.8
Maintenance (6)	X_{max}	1	5	1	10	2.5
Urgent action (7)	X_{min}	1	5	1	2	0.7
Acceleration - seismic hazard (9A)	X_{min}	0.2	4	0.5	200	0.5

The SIEA question on the need for urgent action consists of two parts. The response to the first part determines whether or not there is a need for urgent action. If the expert believes there is such a need (see Section 3.1.1), the second part of the question determines the extent of possible damage if no action is taken. Therefore, only the rating provided in this second part is used in the computation of the DV index. Because the need for urgent action is by definition associated to a high level of risk, an ascending concave value function with a very pronounced curvature is used to transform the corresponding rating into a homogenised vulnerability score (see Fig. 6(c)). In addition, in case the need for urgent action is identified, the homogenised score linked to it contributes to 90% of the final DV index value (see Fig. 7). These two measures ensure that the final DV and DR index values are high even if only a small fraction of the structure is likely to be affected if no urgent action is taken. If it is deemed that no urgent action is required, the weight attributed to the urgent action criteria is set to 0 and the eliminated weight is redistributed proportionally among the remaining criteria in the first level of the hierarchical structure of the DV index.

In fact, at any level of the DV index, if no information is available on a particular criteria, the weight attributed to it is set to 0 and the eliminated weight is redistributed proportionally among all remaining criteria at the same level connected to the same parent criteria. This axiom is established for the DV index because the best estimate of damage vulnerability can always only be based on available information and investigations carried out. This is in stark contrast to the mechanism behind the LoK index whereby no information from a particular activity deemed as being relevant represents a lack of knowledge. As such, as described in Section 4, the weights among different criteria at different levels of the LoK index can only change if the rankings and ratings provided in the second part of the SIEA are changed.

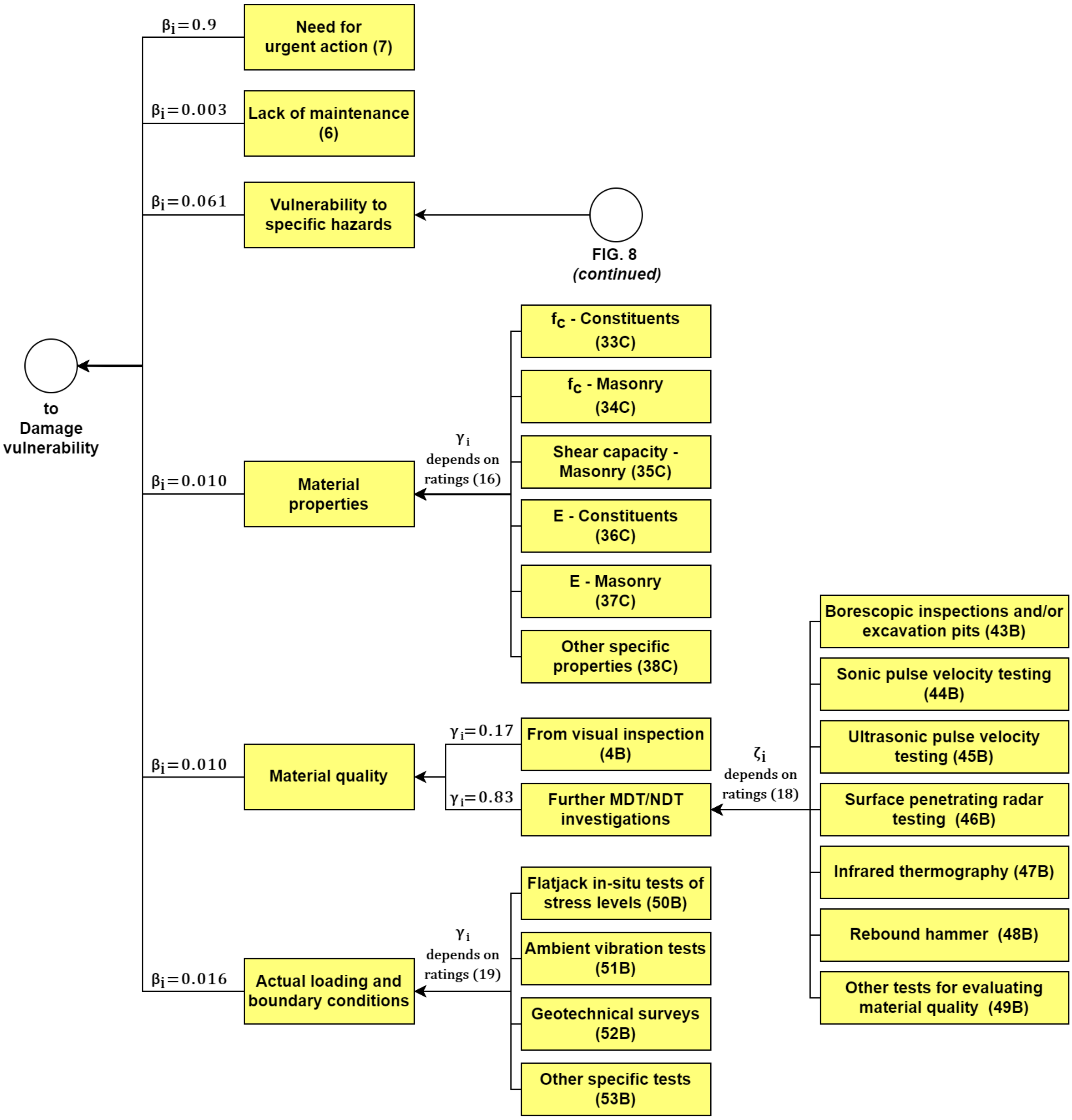


Figure 7: Criteria tree for the damage vulnerability index. The relevant question references are shown in brackets at the end of each branch. Parameters β_i, γ_i, and ζ_i refer to relevant weights that need to be applied to criteria at the second, third, and fourth hierarchical level of the global damage risk index respectively.

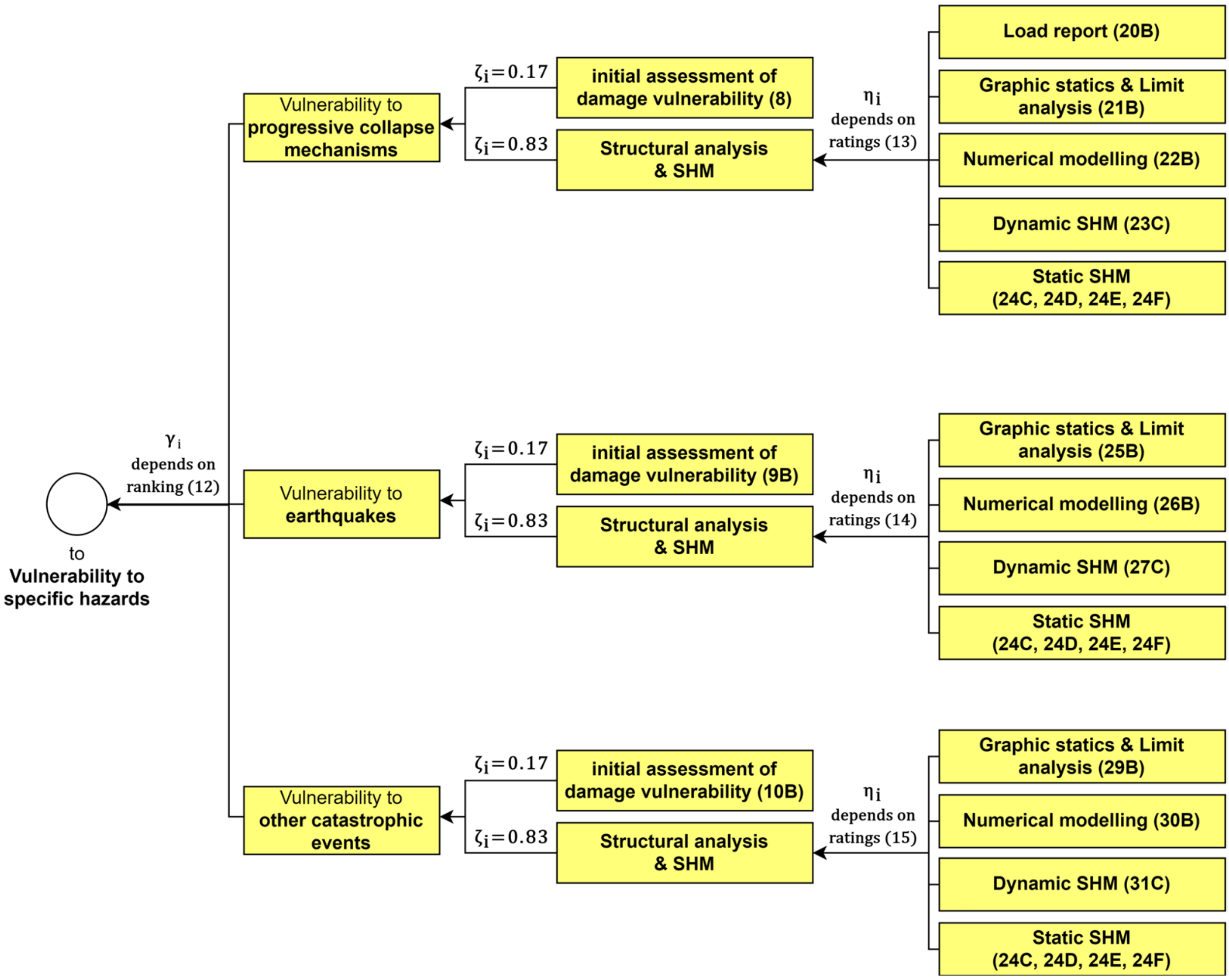


Figure 8: Criteria tree for the sub-indicator linked to the assessment of specific vulnerabilities. The relevant question references are shown in brackets at the end of each branch. Parameters γ_i, ζ_i, and η_i refer to relevant weights that need to be applied to criteria at the third, fourth, and fifth hierarchical level of the global damage risk index respectively.

For cases not requiring urgent action, much of the hierarchical structure of the DV index can be explained in terms of the structure of the LoK index. It is clear that information on the material or from in-situ tests of actual conditions are invaluable to inform structural analysis methods and to ensure that mathematical models employed provide an accurate representation of reality. In addition, they can also often provide some indications on the general vulnerability to damage. However, unlike structural analysis and SHM, most of these activities cannot be tailored to specifically evaluate the vulnerability to distinct hazards. This explains why the vulnerability criteria scores associated to material properties, material quality, and in-situ tests are combined in the first level of the DV index, as shown in Fig. 7. The weights assigned to each of these three groups are the same as that assigned to the corresponding groups when computing the LoK index. As described in Section 4, this is because the weights are assigned in the LoK index based on the possible information that each activity group can provide for global damage vulnerability assessment. In fact, the consistency between the two indices is vital for them to provide meaningful insights when used jointly for decision-making. As such, for these three activity groups, the subsequent hierarchical levels have the same structural organisation as the corresponding parts of the LoK index and weights which depend on ratings provided in the second part of the SIEA are computed in a similar way using Eq. (3). However, as previously mentioned, in the case of the DV index, if no information is available on a particular criteria, its relevance factor is set to 0 and weight redistribution is carried out at that level. Of course, answers to questions related to damage vulnerability are used to compute the criteria scores instead of those relating to the level of knowledge.

According to the activity groups defined in this research, since the contribution of material characterisation and in-situ tests have already been considered, the remaining criteria in the first level of the DV index must be based on historical information, geometry and damage surveys, structural analysis, and SHM. Excluding the special case of the need for urgent action, which has already been addressed, the remaining criteria include the maintenance condition and the outcome of specific studies carried out to evaluate the vulnerability to specific hazards (see Fig. 7). As such, to maintain the consistency with th LoK index, the sum of the weights of these two criteria in the first level of the DV index must be equal to the sum of the weights attributed to the aforementioned remaining activity groups in the LoK index. This corresponds to a total weight of 64% that has to be divided between the two criteria. Although the maintenance condition can definitely play an important role in defining the rate of change related to decay and deterioration processes, it is seldom the true underlying cause of these processes. In most circumstances, the true cause of these can be related to environmental effects and mechanical actions. In the context of this research, a better understanding of the effects of these underlying causes is considered as being much more significant for an accurate vulnerability assessment. As such, when no urgent action is required, only 3% of the DV index value is determined by the criteria representing the damage vulnerability linked to a lack of maintenance (see Fig, 7). This represents 5% of the 64% left to be distributed after considering the contribution of material characterisation activities and tests of in-situ conditions.

Consequently, 61% of the DV index value relies on evaluations of the damage vulnerability to specific hazards. This criteria in turn depends on individual assessments of the vulnerability to progressive collapse mechanisms, to earthquakes, and to other catastrophic events. As shown in Fig. 8, the weights assigned to each of these depend on the responses and rankings provided in question 12 of the SIEA. As described in Section 4, the first, second, and third ranked specific vulnerabilities are attributed weights of 71.7%, 20.5%, and 7.8% respectively. Naturally, if the choice is made during the SIEA to exclude the vulnerability to a specific hazard from the assessment, weights are redistributed proportionally among the remaining specific vulnerabilities based on how they have been ranked. As shown in Fig. 8, each of the three identified specific vulnerabilities relies on an initial assessment and on the conclusions that could be drawn from the application of structural analysis and SHM. Because the initial assessment is made on the basis of historical information and data collected through geometry and damage surveys (see Section 3.1.1), the weights assigned to these specific activity groups in the LoK index can be used to derive the weight that needs to be assigned to the initial assessment component of each specific vulnerability. In the LoK index, the combined weight of the activity groups related to historical information and geometry and damage surveys amounts to 11% (see Table 1). This represents 17% of the sum of the combined weight of these two activity groups with structural analysis and SHM in the LoK index. Therefore, as shown in Fig. 8, 17% of the score of each criteria related to a specific vulnerability is attributed to the initial assessment while the remaining 83% are based on the conclusions from structural analysis and SHM. The weight attributed to each activity contributing to each structural analysis and SHM criteria is then derived using the ratings provided during the SIEA in a similar way as it is done for the LoK index.

The vulnerability score attributed to each specific initial assessment comes directly from relevant ratings given during the first part of the SIEA. As described in Section 3.1.1, results from existing simplified assessment methodologies can be used as a basis for providing these ratings. The range of each rating has been designed so that no additional transformation is needed to convert it into a homogeneous vulnerability score before it can be compounded into the DV index.

In fact, the range of most ratings used to compute the DV and DR indices have been designed so that they can be directly compounded without requiring an additional transformation. Exceptions include the four questions from the first part of the SIEA shown in Fig. 6, all questions providing a material quality rating, and processed results from static SHM.

5.1.2. Automatic updating of index values from static SHM data

For the case of static SHM, as mentioned in Section 3.2, the proposed risk assessment methodology can take advantage of results from the automated data analysis procedure described in [35] to automatically update the DV index. Four key processed results are utilised for this purpose: the percentage of monitored parameters classified as evolutionary and the average growth rate of monitored crack widths, distances, and inclinations classified at least as apparently evolutionary. If the automated data analysis procedure is not used, reasonable estimates for these values have to be provided to update the DV index. These four processed results are then converted to a homogenised vulnerability score according to the value functions shown in Fig. 9. These have been constructed based on observations made from the monitoring of 18 crack widths, 6 distances, and 4 inclinations in two complex medieval structures [35]. The duration of available monitoring data from these sensors varied between 2 to 5 years, and the data acquired have already been used to draw meaningful conclusions for the vulnerability assessment of the two structures. In addition, the value function for transforming monitored inclinations has been designed so that a vulnerability score of 5 is attributed to an inclination that would correspond to an apex displacement of 0.15 m after 10 years of a 10 m block experiencing rigid rotation. On the other hand, a score of 1 is attributed to an inclination corresponding to an apex displacement of 0.01 m after 10 years with the same assumptions.

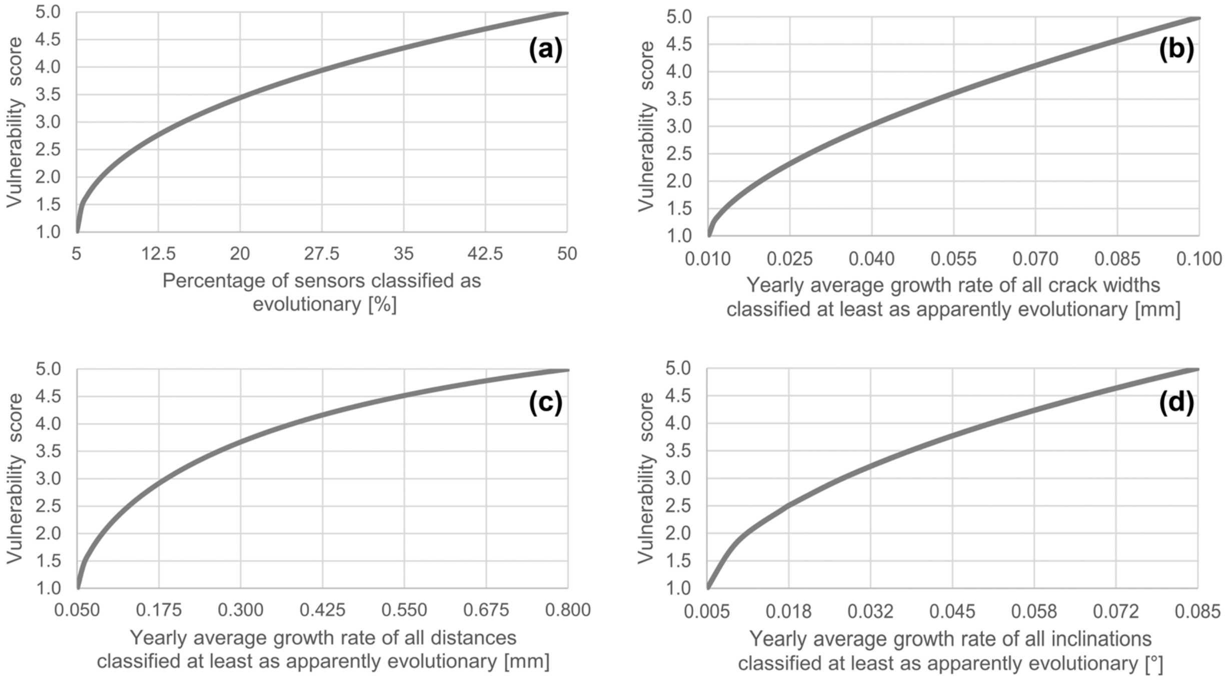


Figure 9: Value functions converting processed results from static SHM to homogenised vulnerability scores to be combined in the damage vulnerability index. Specifically, the functions shown are used to transform the percentage of sensors classified as evolutionary (a) and the average growth rate of monitored crack widths (b), distances (c), and inclinations (d).

Table 4: Parameters used in Eq. (1) to derive value functions for converting processed results from static SHM into vulnerability scores.

	X^*	X_{min}	X_{max}	m_i	n_i	A_i
Percentage evolutionary (24C)	X_{min}	5	50	1	600	0.5
Crack widths (24D)	X_{min}	0.01	0.1	0.5	200	0.62
Distances (24E)	X_{min}	0.05	0.8	8	10	0.65
Inclinations (24F)	X_{min}	0.005	0.085	4	6	0.6

All the value functions used for transforming static SHM results can be defined by substituting the parameters listed in Table 4 into Eq. (1). They are all implemented as conditional functions so that all original responses lower than X_{min} (see Eq. (1)) are given a vulnerability score of 1 while all responses greater than X_{max} (see Eq. (1)) are given a score of 5.

The final homogenised vulnerability score based on information from static SHM is computed as a weighted sum with 50% attributed to the score related to the percentage of monitored parameters classified as evolutionary while the remaining 50% is distributed equally among the scores linked to crack widths, distances, and inclinations.

5.1.3. Computation of the DV index

Once all relevant inputs have been converted to homogenised scores, the DV index can be simply computed as shown in Eq. (5).

$$DV\,index = \sum_{i=1}^{N} \beta_i \cdot \gamma_i \cdot \zeta_i \cdot \eta_i \cdot S_{DV,i} \tag{5}$$

Where $S_{DV,i}$ refers to the score of a particular criteria at the end of one of the branches of the hierarchical structure shown in Figs. 7 and 8, while β_i, γ_i, ζ_i, and η_i refer to the weights that need to be applied at every level. If a criteria is found at the end of a branch ending after the first level, γ_i, ζ_i, and η_i should be considered as 1. Similarly, if a criteria is found at the second level, ζ_i and η_i should be considered as 1 while only η_i should be considered as 1 for criteria found at the third level. N refers to the number of individual criteria that are ultimately considered for the computation of the index. This can change depending on what diagnosis activities have actually been carried out. If all the possible diagnosis activities identified are used, $N = 36$.

5.2. Computation of the DR index

As described in Eq. (6), once the DV index has been computed, the DR index can be obtained through a weighted sum of the DV index value and the scores related to Hazard and Exposure levels.

$$DR\,index = \sum_{i=1}^{6} \alpha_i \cdot \beta_i \cdot S_{DR,i} \tag{6}$$

Where $S_{DR,i}$ refers to the score of each criteria at the end of every branch of the hierarchical structure shown in Fig. 5, while α_i and β_i refer to the weights applied at every level. Naturally, since the DV index is found at the first level of the hierarchical structure, β_i is taken as 1 for this criteria.

6. From risk assessment to decision making

A significant advantage of the proposed risk assessment methodology is that it allows a systematic updating of the risk assessment every time a relevant risk mitigation action is taken. This can include a temporary emergency intervention, more permanent structural interventions, an improvement to the maintenance plan, or even specific measures taken to reduce the fire hazard. The methodology also relies on a systematic process for updating the risk assessment after performing diagnosis activities aimed at better characterising damage vulnerability. In both cases, the update is achieved through answers to standard questions that must be provided by the expert responsible for risk assessment. These answers are then used to update the two key indices proposed to facilitate the decision-making task: one related to the level of knowledge on damage vulnerability and the other to the estimated risk level.

For the case of diagnosis activities, only questions relating to the particular activities carried out need to be answered. These will normally consist of one part to evaluate the comprehensiveness of the investigations, and another related to estimated vulnerability levels. An exception to this is the case of static SHM. In this case, after an initial configuration, both indices can be periodically updated automatically by taking advantage of processed results from the methodology described in [35].

After an improved maintenance plan has been implemented, the response to the question on maintenance condition provided in the SIEA needs to be updated. Similarly, after specific measures are taken to reduce the fire hazard, only the single response to the question on this aspect must be updated. If an emergency intervention is carried out, the response to the SIEA question on the need for urgent action needs to be updated. In addition, ratings provided in the SIEA as initial assessments of the perceived vulnerability may need to be updated to reflect the new safety level. These must also be updated every time any structural intervention is carried out. These specific evaluations of the vulnerability to progressive collapse mechanisms, to earthquakes, and to other catastrophic events are based on available historical information and on geometry and damage surveys. In fact, both the level of knowledge and damage vulnerability ratings associated to all diagnosis activities previously performed must be updated to reflect what is known about the new structural condition. This means that the LoK score of a previously applied diagnosis activity can return to 0 if it provides absolutely no information on the new condition of a strengthened structure. As such, the value of the LoK index can decrease after interventions have been carried out. This aspect of the proposed methodology is meant to encourage the design of interventions whose efficiency can be verified and evaluated through rigorous scientific methods.

Because questions that need to be answered can vary depending on the situation and on previous answers, it is vital that the computation and consultation of the indices be implemented as a user-friendly interactive computer program. This strategy will greatly facilitate data entry, and allows necessary updates to be made with ease after relevant actions have been carried out. The computer program should be accompanied by a short manual which includes a brief description of the capabilities of all possible diagnosis activities considered by the proposed risk assessment methodology.

A very useful output of such a program can be a list of relevant diagnosis activities ordered according to their possible contribution to the global level of knowledge. These possible contributions can change depending on the initial evaluation made by the expert and on activities that have already been carried out. Because of the way the LoK index is computed, the possible contribution of any activity considered can easily be calculated. The maximum possible increase of the final LoK index value that can be caused by performing a diagnosis activity can be calculated as the remaining homogenised LoK score that can be attributed to the activity multiplied by all the relevant weights at every level connecting it back to the final index value. The possible contribution of that particular activity is then obtained by dividing this maximum possible increase by the difference between the maximum LoK index value and the current index value. Table 5 shows the values of this possible contribution if a LoK score of 0 is attributed to each activity and equal ratings are assigned to all of them during the SIEA.

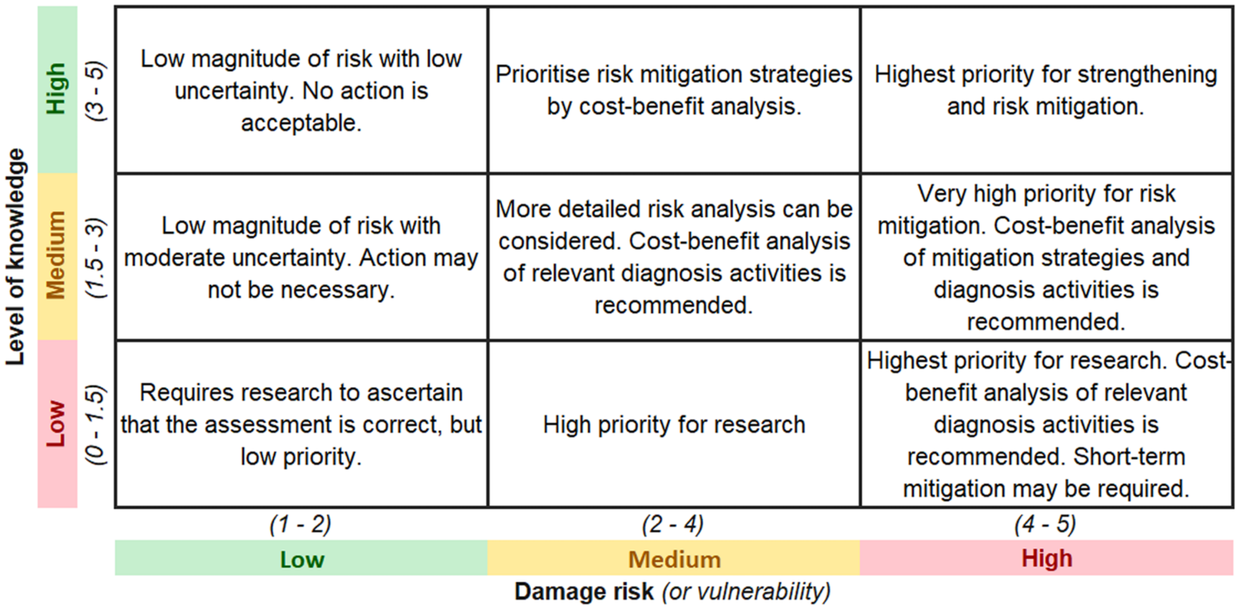
Table 5: Diagnosis activities that can be listed according to their remaining possible contribution to the level of knowledge on damage vulnerability.

Diagnostic activity	**Activity group**	**Possible contribution to level of knowledge indicator***
Graphic statics & Limit analysis	Structural analysis & SHM	11.2%
Numerical modelling		11.3%
Dynamic SHM		11.3%
Static SHM		11.3%
Load report		7.6%
Flatjack in-situ tests of stress levels	Actual loading & boundary conditions	4.0%
Ambient vibration tests		4.0%
Geotechnical surveys		4.0%
Other specific in-situ tests		4.0%
More information on Geometry	Geometry & damage surveys	3.7%
More information on Damage		3.3%
Compressive strength - Constituents	Material properties	1.7%
Compressive strength - Masonry		1.7%
Shear capacity - Masonry		1.7%
Elastic modulus - Constituents		1.7%
Elastic modulus - Masonry		1.7%
Other material properties		1.7%
Pits/inspections	Material quality	1.2%
Sonic pulse velocity testing		1.2%
Ultrasonic pulse velocity testing		1.2%
Surface penetrating radar		1.2%
Infrared thermography		1.2%
Rebound hammer		1.2%
Other tests of material quality		1.2%

* If equal weights are assigned among activities at each category level during the Standardised Initial Expert Appraisal(SIEA).

It can be helpful for the expert performing risk assessment to consult this dynamic list after updating index values to ensure that the importance attributed to key activities are in line with what can be expected. This can even be used as a basis for fine-tuning provided ratings. Eventually, the list can prove to be useful for selecting the most suitable methods for further investigations and for communicating why particular diagnosis activities are being recommended. It can also provide valuable information to inform cost-benefit analyses. Some diagnosis activities such as SHM can be quite expensive and almost always require some form of cost-benefit analysis before their implementation. However, although costs can be estimated accurately, it can be very difficult to obtain quantitative information on the expected benefits. The potential contribution to the LoK index can serve this purpose. Of course, since the indices are only meant to be approximate tools to help inform decision-makers, the specific needs of each case should be considered and the decisions on the best research activities to conduct should not be based only on the index values.

The main aim of the two indices computed as part of the proposed risk assessment methodology is to help decision-makers to evaluate the current level of risk and the uncertainty associated to this estimation. The proposed approach thus promotes risk mitigation decisions that make efficient use of resources. The decision matrix shown in Fig. 10 demonstrates how the two indices can be used jointly to decide on the best course of action for preserving a masonry heritage structure. Indicative ranges of the LoK and DR indices are also shown. Because the DV index is more sensitive to changes in the evaluation of the structural condition, decision-makers can also choose to jointly examine the LoK and DV indices in a similar fashion before making a decision. Once again, it is important to stress that the proposed methodology is not designed with the aim of automating decisions. The proposed decision grid can therefore not be used blindly without properly understanding the assumptions behind the computation of the indices.



Level of knowledge		**Damage risk** *(or vulnerability)*: **Low** *(1 - 2)*	**Medium** *(2 - 4)*	**High** *(4 - 5)*
High	*(3 - 5)*	Low magnitude of risk with low uncertainty. No action is acceptable.	Prioritise risk mitigation strategies by cost-benefit analysis.	Highest priority for strengthening and risk mitigation.
Medium	*(1.5 - 3)*	Low magnitude of risk with moderate uncertainty. Action may not be necessary.	More detailed risk analysis can be considered. Cost-benefit analysis of relevant diagnosis activities is recommended.	Very high priority for risk mitigation. Cost-benefit analysis of mitigation strategies and diagnosis activities is recommended.
Low	*(0 - 1.5)*	Requires research to ascertain that the assessment is correct, but low priority.	High priority for research	Highest priority for research. Cost-benefit analysis of relevant diagnosis activities is recommended. Short-term mitigation may be required.

Figure 10: Decision matrix adapted from [76] demonstrating how the proposed indices can be used to facilitate decisions.

7. Application to Mallorca cathedral

A complex case study has been chosen to demonstrate the usefulness of the proposed risk assessment methodology. The cathedral of Santa Maria in Palma de Mallorca (Fig. 11) can definitely be considered as one of the most remarkable monuments built in the so-called Catalan Gothic style. It boasts grand proportions and structurally audacious piers with slenderness ratios that can be twice that of many comparable Gothic cathedrals. Having been built over a period of 300 years, the cathedral has a very complex structural scheme consisting of the interaction of several different parts. It has been the subject of numerous studies and scientific investigations of relevance for characterising damage risk and has in part been chosen as a case study because both the details and conclusions of these studies are well reported in literature [28, 35, 48, 94–101]. In addition, data collected from a static SHM system over a period of 5 years from 2003 to 2008 had already been processed using the automated data analysis procedure presented in [35]. As such, results from this application could seamlessly be incorporated into the risk assessment through the procedure described in Sections 4 and 5.1.

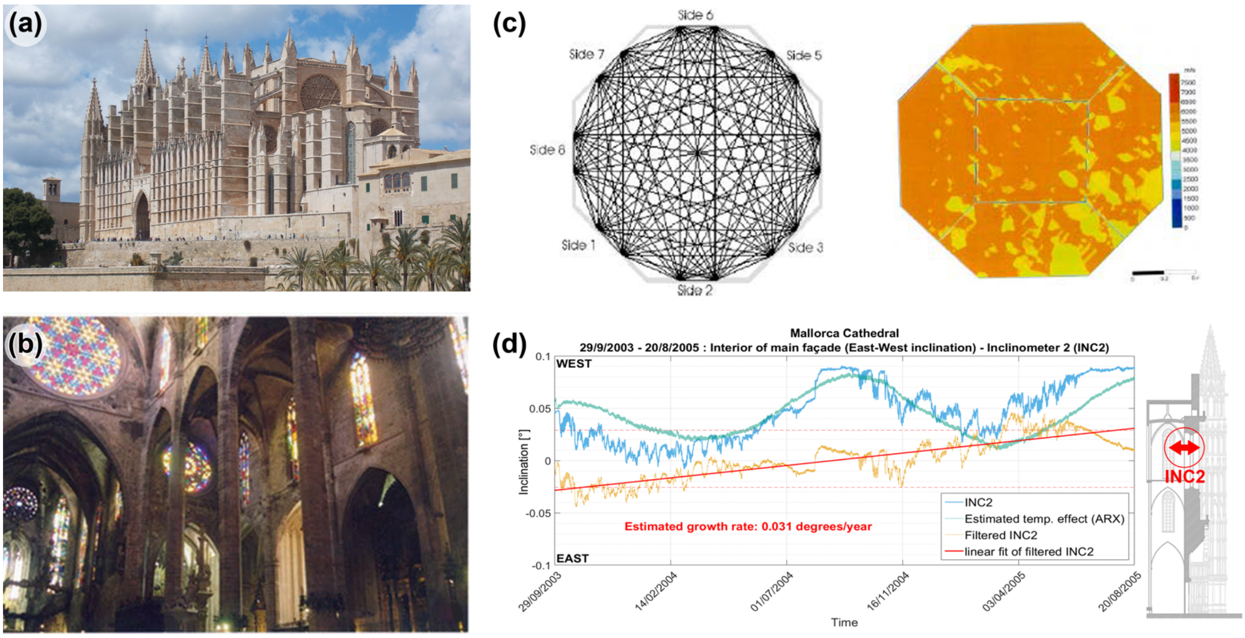


Figure 11: (a) Exterior view of Mallorca cathedral. (b) Interior view of Mallorca cathedral [99]. (c) Sonic tomography of piers [96]. (d) Recorded time series of inclination monitored as part of static SHM system installed in 2003. Filtering of simulated reversible environmental effects and estimation of underlying evolution rate is also shown.

In the case of Mallorca cathedral, much is known on the construction process, on previous structural alterations, and on past damage events thanks to extensive historical research [94, 101]. Similarly, a substantial amount of information is available on existing damages as well on the geometry. This includes reports from visual inspections [97], surveys of the most important pathologies, as well as master plan drawings [94, 101]. The basic information on damage and geometry has been further improved over the years with more accurate or in-depth investigations. In the case of geometry, these investigations have included pits in the roof to reveal a system of masonry walls supporting the terrace floor slab [96], as well as additional topographic and photogrammetry surveys [98, 99]. Various structural analysis methods have also been applied for the diagnosis and safety evaluation of the structure, including graphic statics analyses to evaluate the stability of a transverse bay [48, 101], kinematic analyses of macro elements to evaluate the seismic capacity (limit analysis) [101], and several sophisticated finite element modelling (FEM) approaches to assess the vulnerability to both progressive collapse and earthquakes [48, 98–100]. In addition to the previously mentioned static monitoring system, two different dynamic SHM systems have been installed in the structure, one in 2005 [96] and the other in 2010 [28]. Several investigations have also been carried out to better understand the material quality and variability in several parts of the structure. This includes seismic tomography, surface penetrating radar investigations, thermography investigations, pits in the roof, and the extraction of a core to reveal the inner composition of a buttress [96, 101]. Several investigations have also been carried out to better characterise the actual loading and boundary conditions in-situ. This includes ambient vibration tests used mainly to validate numerical models [28, 96], soil investigations using geophysical techniques, and in-situ determination of work stresses using the hole drilling technique [96]. With respect to material properties, microscopy and diffractometry analyses performed on samples of constituents allowed the identification of different masonry types corresponding to different construction stages [96]. However, with respect to mechanical parameters, the determination of the average material strength has proved to be very difficult due to the risks associated with possible in-situ tests, as well as the inability of extracting large enough specimens [96]. Nevertheless, information about the global stiffness could be obtained by calibrating models with dynamic tests performed in-situ [96].

Although the aforementioned diagnosis activities have been carried out at different points in time, two "knowledge states" have been defined for the purpose of risk assessment to best demonstrate the application of the proposed methodology and to facilitate the interpretation of results:

1. **Initial state:** This state is meant to be representative of the level of knowledge that will typically be available for the risk assessment performed when completing the standardised initial expert appraisal (SIEA). As such, it is assumed that information is only available from historical information and from

initial geometry and damage surveys. With respect to geometry, it is assumed that only information from the historical construction master plan drawings are available in this state.

2. **Final state:** This state is meant to be representative of the current level of knowledge on the structural condition. As such, all the information sources are considered and the final index values depend on SIEA questions as well as on relevant optional questions related to the aforementioned diagnosis activities.

All ratings used to compute the initial and final index values are provided alongside the corresponding question in the appendices. Answers from the SIEA used to compute the initial index values can be found in Appendix A, whereas all answers or updates used to compute the final index values are shown in the subsequent appendices. A level of knowledge (LoK) concavity setting of 2 (see Section 4) was used for computing the LoK indices. The scores of all sub-indicators related to a particular index are always shown using a custom radial diagram such as the ones shown in Fig. 12. In such diagrams, each sector refers to a sub-indicator used to compute the final index value. The central angle of each sector represents its weight in the index, whereas its individual radius shows its score.

The initial and final values of the LoK index for Mallorca cathedral are shown in Fig. 12 together with the LoK scores for each diagnosis activity group. The custom diagrams shown in Fig. 12 are clearly an effective means of transmitting meaningful information on the general level of knowledge used as a basis for risk assessment. In this case, a clear message that can be conveyed through the interpretation of the diagrams is that the current level of knowledge is high for most important aspects of safety evaluation, but that accurate estimation of relevant material properties remains a challenge. In addition, the clear increase in the index value from the initial state can clearly be appreciated, showing how all the diagnosis activities carried out over the years have contributed to a shift from a low level of knowledge on the structural condition to a high one.

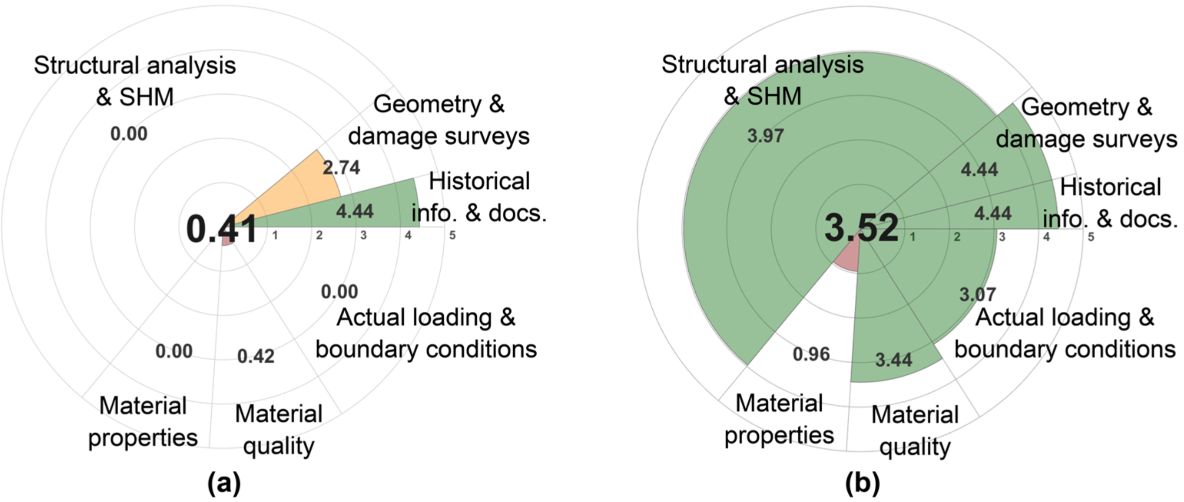
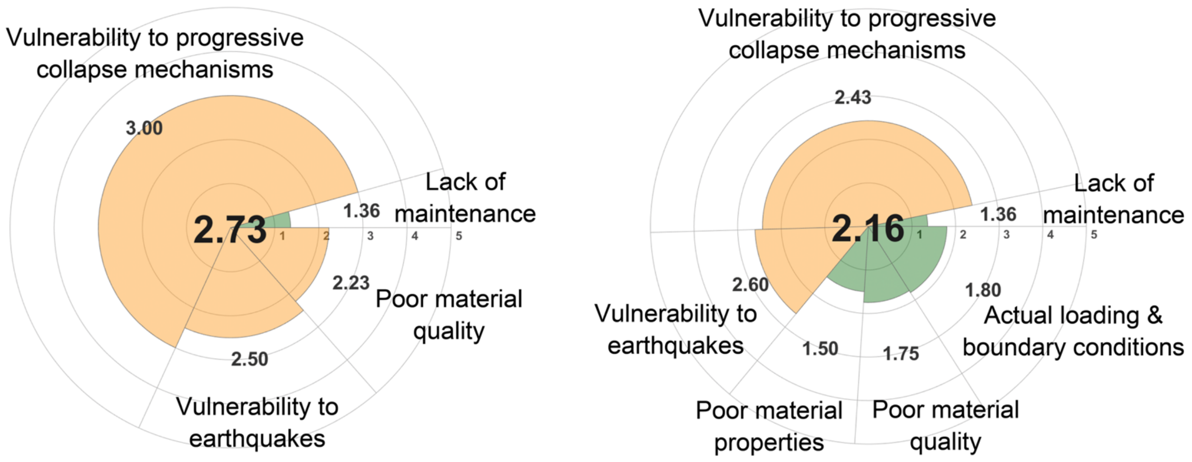


Figure 12: Initial (a) and final (b) values of the level of knowledge (LoK) index for Mallorca cathedral. The LoK scores for each diagnosis activity group are also shown.

With respect to damage vulnerability, preliminary assessments based solely on visual inspections and historical information could definitely lead to the conclusion that there are possible risks of experiencing damage caused by progressive collapse mechanisms. This is mainly due to the significant deformations of the piers and the presence of cracks at the base of columns. However, most structural analysis techniques applied to investigate the safety of the representative bay structure have revealed that significant further damage of critical sections linked to slow deterioration mechanisms is not likely to occur, at least not in the very near future [98, 99, 101]. In addition, NDT has revealed the solid nature and high material quality of the inner core of piers [96]. With respect to the vulnerability to earthquakes, some studies show possible signs of weakness in the longitudinal direction. While it remains true that investigations of seismic capacity indicate a very safe condition, particularly in the transverse direction [98], results from detailed dynamic FEM do indicate that the capacity is lower in the longitudinal direction [28, 101]. Moreover, during a far epicentre earthquake in 2005, records from the earliest dynamic monitoring system installed in the cathedral revealed that the building experienced a certain excitation of its fundamental vibration mode with the largest acceleration amplitudes occurring in the longitudinal direction [95]. It should also be noted that studies attempting to better understand the seismic capacity of the cathedral using limit analysis show that the most likely collapse mechanisms are linked to an outward rotation of the main façade [48, 101]. To add to this fact, recent analysis of static monitoring data indicate that there is possibly an underlying evolutionary trend related to the outward rotation of part of the façade [35]. As such, it can be said that although there are no clear signs of a definite vulnerability to the probable seismic loads that can be expected in the region, the combination of aforementioned observations certainly suggest some specific, albeit localised, vulnerabilities.

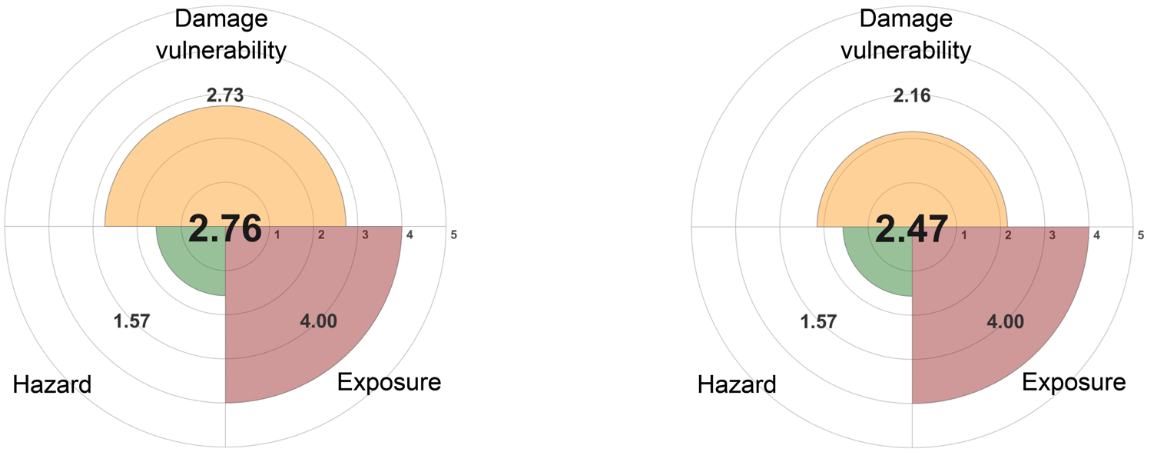
Even if only individual ratings related to specific activities have been provided, most of the general conclusions described in the previous paragraph can clearly be appreciated by examining the differences between the initial and final damage vulnerability (DV) index diagrams shown in Fig. 13. Specifically, there has been a significant decrease in the estimated vulnerability to slowly evolving progressive collapse mechanisms and a very slight increase in the estimated vulnerability to earthquakes.



(a) (b)

Figure 13: Initial (a) and final (b) values of the damage vulnerability (DV) index for Mallorca cathedral. The scores for the first level of vulnerability components are also shown.

The initial and final damage risk (DR) index values for Mallorca cathedral are shown in Fig. 14. Despite the significant decrease in estimated vulnerability, it is clear that the score linked to the exposure component of the DR index adequately fulfils the function of maintaining a more moderate risk level due to the potential loss and the high cultural value associated to this structure.



(a) (b)

Figure 14: Initial (a) and final (b) values of the damage risk (DR) index for Mallorca cathedral. The scores for the first level of risk components are also shown.

The changes in the dynamic list of best activities (see Section 6) from the initial state to the final one are shown in Table 6.

Table 6: Initial and current list of best diagnosis activities to perform in Mallorca cathedral according to the possible contribution of the activity to the level of knowledge (LoK) index.

Initial list of best activities after SIEA		**Current list of best activities**	
Diagnostic activity	**Possible contribution to LoK index**	**Diagnostic activity**	**Possible contribution to LoK index**
Numerical modelling	15.5%	Static SHM	19.0%
Graphic statics & Limit analysis	13.4%	Flatjack in-situ stress tests	9.0%
Static SHM	13.4%	Dynamic SHM	8.6%
Dynamic SHM	9.9%	Compressive strength - Masonry	8.5%
Ambient vibration tests	5.8%	Shear capacity - Masonry	8.5%
Geotechnical surveys	5.8%	Other specific in-situ tests	6.5%
Load report	5.6%	Numerical modelling	4.6%
Sonic pulse velocity testing	3.0%	Compressive strength - Constituents	4.2%
Surface penetrating radar	3.0%	Elastic modulus - Constituents	4.2%
Flatjack in-situ stress tests	2.9%	Graphic statics & Limit analysis	4.1%
Other specific in-situ tests	2.9%	Pits/inspections	3.3%
Compressive strength - Masonry	2.7%	Ambient vibration tests	2.7%
Shear capacity - Masonry	2.7%	Geotechnical surveys	2.7%
More information on Geometry	1.9%	Sonic pulse velocity testing	2.2%
More information on Damage	1.6%	More information on Damage	1.8%
Pits/inspections	1.5%	Surface penetrating radar	1.4%
Infrared thermography	1.5%	Elastic modulus - Masonry	1.3%
Compressive strength - Constituents	1.4%	More information on Geometry	0.9%
Elastic modulus - Constituents	1.4%	Infrared thermography	0.7%
Elastic modulus - Masonry	1.4%	Other material properties	0.6%
Other material properties	1.4%	Load report	0.6%

Some of the most suitable activities suggested at the different stages are along the lines of what can be expected. At the initial stage, versatile structural analysis tools able to evaluate diverse loading scenarios can contribute significantly to the level of knowledge. Because a vast array of such methods have already been applied comprehensively to the study of Mallorca cathedral, it can be deemed reasonable that SHM has more potential at this stage to further improve the understanding of specific vulnerabilities. However, it is very important to note that this list is not based on actual specific hypotheses that need to be investigated by the activity. Such hypothesis and the uncertainty linked to their formulation need to be the most important considerations before the final decision on any investigation is made. Feasibility and associated costs are also very important considerations which cannot be ignored.

The application of the risk assessment methodology to this case study demonstrates how its key outputs can help form a good overview of the general risk situation by considering the combined effect of individual insights drawn from different activities. It also ensures that most relevant criteria are taken into consideration when defining the global risk of damage.

8. Application to other case studies

Besides the application to the very complex case of Mallorca cathedral, three additional case studies are presented to demonstrate how the risk assessment methodology can function under varying conditions of risk, complexity, and information availability.

The specific ratings provided as answers to standard questions and eventually used to compute index values are not provided for all case studies but can be found in [102]. Unlike the case of Mallorca cathedral, no initial "knowledge states" were defined for these case studies and all index scores reflect the evaluation based on the latest information available at the time of performing the risk assessment. A detailed breakdown of the MCDM indices, in terms of the criteria scores in the first hierarchical levels and the weights among them, are presented in Appendix G. The case studies are shown in Figure 15 along with their relative locations with respect to the city of Barcelona and the cathedral of Mallorca.

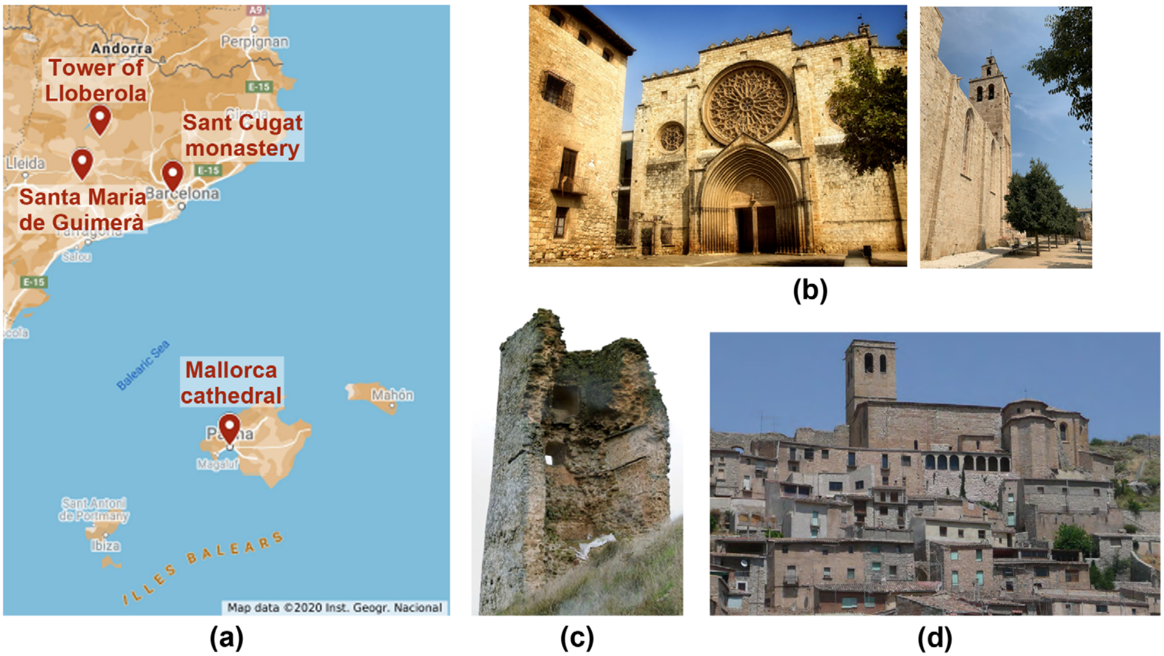


Figure 15: (a) Map showing location of case studies. (b) Sant Cugat monastery. (c) Tower from the remains of the castle of Lloberola [103]. (d) Church of Santa Maria de Guimerà [104].

The first case study, the church of the monastery of Sant Cugat, is currently equipped with a static SHM system which has been installed since 2017 [35]. It is a relatively complex structure since it consists of different parts built over different periods, mostly from the mid-12th century to the 15th century. In addition to the ongoing monitoring campaign, it has also been the subject of several other studies [105, 106]. This knowledge and information combined with on-site visual inspections form the basis used for the risk assessment of this particular case study. The remaining case studies include a medieval tower from the remains of Lloberola castle and the 14th century church of Santa Maria de Guimerà. The risk assessment for these two structures were performed solely based on expert diagnosis reports of their structural condition [103, 104].

The resulting LoK and DR index values for all the case studies after risk assessment are summarised in Table 7. The values of the first level components of the DR index are also shown.

Table 7: Final index values for the structures studied as part of this research.

Case study	LoK index	DV index	Hazard	Exposure	DR index	Curent state & recommendations
Mallorca cathedral	**3.52**	**2.16**	1.57	4.00	**2.47**	Structure has adequate capacity to withstand most foreseeable loads in the near and mid-term future. However, further research is needed to better understand if there is an active deterioration mechanism linked to the outward rotation of part of the facade.
Sant Cugat monastery	**1.75**	**2.44**	1.57	3.50	**2.49**	Structure has adequate capacity to withstand most foreseeable loads in the near future. However, there is definitely an active deterioration mechanism linked to the outward rotation of the bell tower. Further research needed to better understand true cause.
Torre Lloberola	**0.51**	**3.92**	1.46	2.00	**2.83**	Structural intervention in 2017 addressed most urgent needs. However, interventions definitely required to ensure stability in the long-term.
Santa Maria de Guimerà	**1.03**	**3.73**	2.07	2.00	**2.88**	Some works of urgent character required. However, vulnerabilities behind this need are relatively localised.

A substantial amount of information is available for the case of the church of Sant Cugat monastery, including more than 3 years of static monitoring data. In general, it can be said that the structure is in good condition and that there are no significant immediate threats to the global structural integrity. However, as described in a recent paper [35], analysis of monitoring data has confirmed that there is currently an active mechanism linked to the outward rotation of the bell tower. Although the estimated evolution rates do not represent an alarming situation at present, it is undeniable that further study is required to better understand the true cause and nature of this mechanism, and to design adequate interventions to limit possible negative consequences it may have for structural integrity. In fact, several in-situ investigations are already planned to be carried out on this structure, which should lead to an increased level of knowledge for risk assessment.

Of all the case studies considered, the tower from the remains of Lloberola castle definitely represents the structure with the simplest geometrical arrangement. Given the simpler nature of the structure, it can be said that initial investigations contribute more towards exhaustive knowledge when compared to the more complex case studies presented in this section. As such, while the LoK concavity setting was set at 2 for all the other case studies, it was set at 4 for this particular case in order to account for this effect (see Section 4.1). In this case, the main sources of available information were detailed analyses of historical sources and of visible damages [103]. Although it is evident that this structure has suffered from severe deterioration, it must be highlighted that the most urgent matters have been addressed by a recent intervention. Nevertheless, the measures implemented cannot be considered as being sufficient to ensure long-term safety. As such, the vulnerability level can still be considered as being rather high, particularly considering the long run. It should also be mentioned that since no visitors are currently able to visit the structure (to the best of the author's knowledge), the exposure level of this particular structure has been considered as being relatively low compared to the other case studies (see Table 7).

In addition to detailed analyses of historical sources and damages, results from graphic statics analysis of a typical section of the main nave was also available for the case of the church of Santa Maria de Guimerà [104]. For this particular case, the particular location and situation of the structure prompted an investigation into the landslide susceptibility in the area. This information is available with a resolution of 30 m for the entire region of Catalonia thanks to the work presented in [107]. It is known that historic masonry churches can suffer significant damages due to landslides, as evidenced in [108]. As shown in Figure 16, the susceptibility to landslides turned out to be "Moderate" in the precise location of the church, with several adjoining grid cells showing a "High" susceptibility. As a result, this case is the only one for which the specific vulnerability of the structure to other catastrophic events (see Section 3.1.2) was explicitly included in the risk assessment (see Appendix G). Nevertheless, it must be said that the surrounding urban landscape and the fact that a retaining structure was recently reconstructed reduce the hazard of a landslide affecting the precise location of the church.

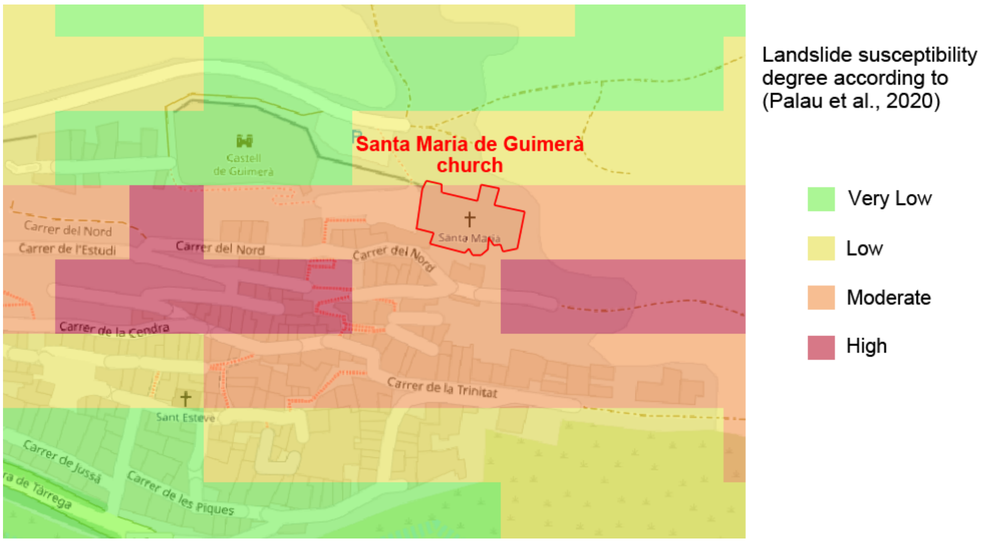


Figure 16: Landslide susceptibility around the church of Santa Maria de Guimerà [107].

With respect to damage vulnerability, it must be said that the church of Santa Maria de Guimerà is generally in a poor state of conservation with certain specific matters requiring immediate attention. The first action required involves adequate control of the lateral thrust imposed by the vaults and arches. This involves the removal of a reinforced concrete cover which possibly exists above the vaults and waterproofing of the roof along with adequate drainage design to prevent rainwater ingress. Another required intervention that can be considered as urgent involves the stabilisation of a nearby external wall which is in a precarious equilibrium state and clearly susceptible to collapse. Although it does not form part of the structure of the church itself, debris from the collapse of this wall could cause significant damage to the church. In addition to these urgent needs, several other interventions could be required to ensure long-term stability. Static structural health monitoring of specific parameters could allow certain phenomena to be better ascertained before making definitive decision on the most suitable interventions required.

In general, it can be said that the index values provide adequate representations of the main conclusions that can be drawn from the risk assessment of the case studies. The LoK indices adequately convey the depth and sophistication of the analyses forming the basis of the risk assessment, and the vulnerability and risk index values are in line with what can be expected based on the descriptions elaborated in previous paragraphs. Nevertheless, it is important to recall that the main purpose of the indices is not to automate decisions but rather to ensure that a thorough and rigorous thought process is behind recommendations, to inform decision makers as concisely and clearly as possible, and to facilitate communication among relevant stakeholders.

That being said, in addition to the useful insights presented by the indices and their accompanying custom radial diagrams, the automatically generated lists of best activities are also in-line with what can be expected and can also provide additional useful insights. Of course, the choice of which action to perform (if any) must ultimately be based on the specific needs of each structure and cannot be based only on the proposed generalised index formulation. A notable observation that can be made is that static SHM is very highly ranked in all the case studies. This stems mainly from the fact that it is a powerful and adaptable tool that can provide useful information to better understand a wide range of structural phenomena. In fact, static SHM turns out to be ranked at the top of the list of possible diagnosis activities for two of the four cases presented in this article. In the case of the tower of Lloberola, it is surpassed by numerical modelling. This is due to the simpler geometry of the structure, which means that the development of useful models can be expected to be more straightforward. In the case of the church of the monastery of Sant Cugat, static SHM is surpassed by several diagnosis activities. This is definitely due to the fact that a relatively comprehensive system is already installed in the structure and has been providing useful and reliable data since more than 3 years. It is interesting to see that most of the diagnosis activities that can now contribute more to the LoK index score, such as numerical modelling and ambient vibration testing, are also activities that can directly be used to better understand the phenomena related to the bell tower, which is the main source of concern for this structure. Finally, it can be observed that the need for more information on existing damage is recurrently found at the bottom of the list of best diagnosis activities as a consequence of the availability of expert damage analyses for the cases studied.

9. Conclusions

This research has proposed a systematic methodology for the risk assessment of masonry heritage structures which relies on the computation of two key indices representing the estimated risk level and the level of knowledge on which the estimation is based. Both indices have been developed using well-established multi-criteria decision making (MCDM) procedures and have been specifically designed to improve the objectivity behind decisions on the preservation of unique masonry heritage structures. These indices should be re-evaluated every time the risk assessment needs to be updated. Most of the information required for the computation of the indices have to be supplied by the expert responsible for risk assessment in the form of standard answers to standard questions. Furthermore, the risk assessment procedure and the assumptions behind the computation of the indices are based on current best practices for the analysis, conservation, and structural restoration of architectural heritage. As such, it is specifically designed so that a dynamic risk assessment is performed, promoting the application of minimum interventions based on a strong scientific basis.

Three main novelties are linked to the proposed risk assessment methodology. The first is that it proposes decision-making tools in the form of standard indices able to consider information from a diverse set of diagnosis activities including structural analysis, structural health monitoring (SHM), damage surveys, material characterisation tests, non-destructive testing (NDT), and specific in-situ tests. The second is that it allows the expert responsible for risk assessment to tailor the hierarchical structures defining the indices according to the unique characteristics of a heritage structure. This is achieved through a systematic hierarchy re-structuring procedure based on rankings and ratings provided by the expert during an initial standardised appraisal. This needs to be carried out after performing an initial analysis of information on damages, geometry, and history collected through inspections and an initial desk study. The third novelty lies in the possibility of automatically updating the index values based on data collected using static SHM systems. This is achieved by taking advantage of processed results from a previously developed automated data analysis procedure [35].

However, it is very important to highlight that the proposed procedure is not meant to automate decisions, but rather to support decision makers and to inform them as clearly and usefully as possible. In fact, for the final indices to provide meaningful insights, it is essential that answers to the standard questions are provided by a professional with sufficient experience and knowledge on the structural diagnosis of masonry heritage structures.

It is envisaged that besides helping decision-making, standard outputs proposed as part of the procedure have the potential to facilitate the communication of key aspects behind recommendations to non-technical stakeholders. While it is clear that risk mitigation measures for masonry heritage structures need to be based on solid scientific evidence and findings, it is often important for non-technical stakeholders to be involved in the decision process. As such, indices which can easily be explained in terms of a decision grid can help communicate the most important technical points for decisions. The communication can be further enhanced with standard outputs, such as radial diagrams showing the composition of index values or dynamic lists of best activities based on their possible contribution to the level of knowledge indicator. In a similar fashion, the proposed risk assessment procedure can be employed to streamline collaboration among experts with different sub-fields of specialisation by providing them with a common framework to share insights on the comprehensiveness of different investigations and on pertinent information for the evaluation of damage risk.

The proposed risk assessment framework can also be seen as an initial step towards incorporating relevant technical aspects related to structural damage into broader decision support systems for heritage. Such integrated systems could eventually help in addressing the increasing need to consider criteria related to sustainability, energy efficiency, and socio-economic impacts for decision-making on heritage.

Conflicts of interest

The authors confirm that there are no known conflicts of interest associated with this publication.

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Appendix A. Standardised Initial Expert Appraisal (SIEA)

Appendix A.1. Initial evaluation of level of knowledge and damage risk

Table A.1: Questions to be answered during the first part of the SIEA. Answers are used to evaluate initial value of indicators related to the level of knowledge and the damage risk. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	**Question**	**Answer range**	**Case study**
	Historical information and documentation (level of knowledge)		
1	Please rate the quality and comprehensiveness of information available on the following topics:		
1A	The construction process.	(0 - 5)	4.5
1B	Historical structural alterations.	(0 - 5)	4
1C	Past structural interventions.	(0 - 5)	4.5
1D	Past damage events (Fires, earthquakes, destructive events).	(0 - 5)	4
	Geometry & damage surveys (level of knowledge)		
2	Please rate the quality and quantity of information available on the geometry of the structure.	(0 - 5)	2.5
3	Please rate the accuracy and comprehensiveness of information available for damage analysis.	(0 - 5)	3
	Initial material quality (level of knowledge and damage vulnerability)		
4A	Please rate the level of accessibility to all the different materials of the structural system during visual inspections?	(0 - 5)	2
4B	How would you rate the overall integrity and quality of the masonry material based on visual inspections?	(1-5)	3
	Exposure		
5A	Please rate the level of exposure in terms of the cultural value that the structure represents.	(1-5)	4
5B	Please rate the level of exposure in terms of usage and potential loss.	(1-5)	4
	Lack of maintenance (damage vulnerability)		
6A	How would you describe the state of maintenance of the structure?	(1-5)	3
6B	Please rate the suitability of the current maintenance plan to address visible pathologies.	(1-5)	3
	Need for urgent action (damage vulnerability)		
7A	Are there clear signs that urgent action is required to stabilise the structure?	0 or 1	0
7B	How much of the structure is likely to be affected if no urgent action is taken	(1-5)	NA
	Progressive collapse mechanisms (damage vulnerability)		
8	Based on available historical information, damage inspections, and reasonable engineering judgement, please rate the perceived susceptibility of the structure to experience significant damage due to progressive collapse mechanisms.	(1-5)	3
	Earthquakes (hazard and damage vulnerability)		
9A	What is the peak ground acceleration with a 10% probability of exceedance in 50 years? $[m/s^2]$	≥ 0 m/s^2 (1-5)	0.4 m/s^2 (1.9)
9B	Based on the information available about past performance to historical earthquakes, as well as the evidence on the structure in terms of damage, please rate how concerning is the perceived vulnerability of the structure to earthquakes.	(1-5)	2.5
	Other catastrophic events (hazard and damage vulnerability)		
10A	Please rate the hazard of other catastrophic events in terms of their potential intensity and frequency of occurrence?	(1-5)	1
10B	Based on available historical information, damage inspections, and reasonable engineering judgement, please rate how concerning is the perceived vulnerability of the structure to other potential catastrophic events.	(1-5)	1
	Fire hazard		
11	Please rate the fire hazard in terms of possible sources of ignition, available fuel and potential for fire to spread.	(1-5)	2.5

Table A.2: Description of the significance of the different values that can be attributed to each question in the first part of the SIEA.

Question ref.	**Range description**
	Historical information and documentation (level of knowledge)
1A - 1D	**0:** No information; **1:** Very Poor; **2:** Poor; **3:** Fair; **4:** Good; **5:** Excellent
	Initial geometry & damage surveys (level of knowledge)
2	**0:** No geometrical information; **1:** Limited, possibly unreliable, idea of general dimensions; **2:** Measurements of some key dimensions, no verification of inclinations; **3:** Measurements of most key dimensions, some inclination verifications; **4:** Comprehensive set of measurements and/or drawings, some investigations on dimensions of hidden elements; **5:** Comprehensive reliable set of drawings, comprehensive knowledge on dimensions of hidden elements
3	**0:** No visual inspection, no information on damage; **1:** Many critical areas could not be inspected, no damage summary; **2:** Many critical areas could be inspected, some damage summary or mapping; **3:** Most critical areas could be inspected, good damage mapping; **4:** All critical areas could be inspected, mapping of most significant damages; **5:** All areas could be inspected, comprehensive mapping of all significant cracks and damages
	Initial material quality (level of knowledge and damage vulnerability)
4A	**0:** No visual inspection carried out; **1:** Very poor. Many critical areas are not accessible, structural elements have complex multi-leaf morphologies, very heterogenous material.; **2:** Poor. Many critical areas are not accessible, structural elements have multi-leaf morphologies, heterogenous material; **3:** Moderate. Many critical areas are accessible, structural elements have multi-leaf morphologies, mostly homogeneous material; **4:** Good. Most critical areas are accessible, structural elements have single-leaf morphologies, mostly homogeneous material; **5:** Very good. All areas are accessible, simple single-leaf wall morphologies, very homogenous material
4B	**1:** Very poor quality, large variability. Material clearly vulnerable to more damage; **2:** Poor quality ; **3:** Moderate quality; **4:** High quality; **5:** Very high quality, very uniform material
	Exposure
5A	**1-2:** Listed in regional or provincial heritage registers; **2-4:** Listed in national heritage register; **5:**UNESCO World Heritage site
5B	**1:** Very low number of vistors and very low potential value of loss; **2:** Low number of vistors and low potential value of loss; **3:** Moderate number of visitors and moderate potential value of loss; **4:** High number of vistors and high potential value of loss; **5:** Very high number of visitors and very high potential value of loss
	Lack of maintenance (damage vulnerability)
6A	**1:** Poor; **2:** Fair; **3:** Good; **4:** Very good; **5:** Excellent
6B	**1:** Minimal maintenance; **2:** Irregular and unorganised maintenance plan; **3:** Maintenance plan addresses only some pathologies; **4:** Maintenance plan appropriate for most visible pathologies; **5:** Comprehensive and detailed tailored maintenance plan
	Need for urgent action (damage vulnerability)
7A	**0:** No; **1:** Yes
7B	**1:** A tiny fraction; **2:** A small fraction; **3:** A moderate fraction; **4:** A substantial fraction; **5:** All or most of the structure
	Progressive collapse mechanisms (damage vulnerability)
8	**1:** Very low (good condition, minimal damages); **2:** Low; **3:** Medium; **4:** High; **5:** Very high (major damages implying stability problems)
	Earthquakes (hazard and damage vulnerability)
9A	Specific value function
9B	**1:** Very low; **2:** Low; **3:** Moderate; **4:** High; **5:** Very high
	Other catastrophic events (hazard and damage vulnerability)
10A	**1:** Possibly some low intensity events which can rarely occur; **2:** Some low intensity events occurring occasionally; **3:** Frequent occurrence of low or medium intensity events or possible rare occurrence of high intensity event; **4:** High probability of occurrence of high intensity event; **5:** Very high probability of occurrence of high intensity events
10B	**1:** Very low; **2:** Low; **3:** Medium; **4:** High; **5:** Very high
	Fire hazard
11	**1:** Very low hazard; **2:** Low hazard; **3:** Moderate hazard; **4:** High hazard; **5:** Very high hazard

Appendix A.2. Evaluation of which activities can best inform the assessment of damage vulnerability

Table A.3: Ratings given in the second part of the SIEA. They are used to assign weights to the contribution of different diagnosis activities to the level of knowledge indicator. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	**Question**	**Answer range**	**Case study**
	Ranking the importance of vulnerability to specific hazards for global vulnerability assessment		
12A	Should earthquakes be included in the vulnerability assessment?	0 or 1	1
12B	Should other catastrophic events be included in the vulnerability assessment?	0 or 1	0
12C	Please rank the following possible 3 aims of structural analysis according to their importance for global damage vulnerability characterisation:		
12C(i)	Structural analysis aimed at better understanding vulnerability to progressive collapse mechanisms	1,2 or 3	1
12C(ii)	Structural analysis aimed at better understanding vulnerability to earthquakes	1,2 or 3	2
12C(iii)	Structural analysis aimed at better understanding vulnerability to other identified catastrophic events	1,2 or 3	NA
	Structural analysis and structural health monitoring - Progressive collapse mechanisms		
13	Please rate to what extent information from the following diagnosis activities can help assess the structure's vulnerability to progressive collapse mechanisms.		
13A	Load report	0,1 or 2	1
13B	Graphic statics & Limit analysis	0,1 or 2	2
13C	Numerical modelling (including FEM, DEM, AEM)	0,1 or 2	2
13D	Dynamic SHM	0,1 or 2	1
13E	Static SHM	0,1 or 2	2
	Structural analysis and structural health monitoring - Earthquakes		
14	Please rate to what extent information from the following diagnosis activities can help assess the structure's vulnerability to earthquakes		
14A	Graphic statics & Limit analysis	0,1 or 2	1
14B	Numerical modelling (including FEM, DEM, AEM)	0,1 or 2	2
14C	Dynamic SHM	0,1 or 2	2
14D	Static SHM	0,1 or 2	1
	Structural analysis and structural health monitoring - Other catastrophic events		
15	Please rate to what extent information from the following diagnosis activities can help assess the structure's vulnerability to other catastrophic events		
15A	Graphic statics & Limit analysis	0,1 or 2	NA
15B	Numerical modelling (including FEM, DEM, AEM)	0,1 or 2	NA
15C	Dynamic SHM	0,1 or 2	NA
15D	Static SHM	0,1 or 2	NA

Table A.4: Ratings given in the second part of the SIEA. They are used to assign weights to the contribution of different diagnosis activities to the level of knowledge indicator. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	**Question**	**Answer range**	**Case study**
	Material properties		
16	Please rate to what extent information from the following activities can help assess the structure's damage vulnerability		
16A	Experimental characterisation of compressive strengths of constituents	0,1 or 2	1
16B	Experimental characterisation of compressive strength of masonry	0,1 or 2	2
16C	Experimental characterisation of shear load-bearing capacity of masonry	0,1 or 2	2
16D	Experimental characterisation of elastic moduli of constituents	0,1 or 2	1
16E	Experimental characterisation of elastic modulus of masonry	0,1 or 2	1
16F	Experimental characterisation of chemical composition and/or other specific material properties	0,1 or 2	1
	Additional geometry and damage mapping activities		
17	Please rate to what extent the following activities can help improve the level of knowledge on the existing geometry and damage		
17A	Topographic surveys (including laser scanning, photogrammetry, or equivalent)	0,1 or 2	2
17B	Borescopic inspections and/or excavation pits	0,1 or 2	0
17C	Impact-echo testing	0,1 or 2	0
17D	More accurate or extensive survey of damages	0,1 or 2	2
	Additional diagnostic activities for assessment of material quality (MDT/NDT)		
18	Please rate to what extent the following activities can help to assess the material quality		
18A	Borescopic inspections and/or excavation pits	0,1 or 2	1
18B	Sonic pulse velocity testing (including tomography)	0,1 or 2	2
18C	Ultrasonic pulse velocity testing	0,1 or 2	0
18D	Surface penetrating radar testing	0,1 or 2	2
18E	Infrared thermography	0,1 or 2	1
18F	Rebound hammer	0,1 or 2	0
18G	Other specific tests for evaluating material quality and condition	0,1 or 2	0
	In situ evaluation of actual loading and boundary conditions		
19	Please rate to what extent information from the following activities can help assess the structure's damage vulnerability		
19A	Flatjack in-situ tests of stress levels	0,1 or 2	1
19B	Ambient vibration tests	0,1 or 2	2
19C	Geotechnical surveys	0,1 or 2	2
19D	Other specific tests	0,1 or 2	1

Table A.5: Explanation of possible ratings.

Question ref.	**Range description**
	Ranking the importance of vulnerability to specific hazards for global vulnerability assessment
12A, 12B	**1:** The vulnerability to earthquakes (or other catastrophic events) is explicitly considered in the assessment. Ratings will have to be given on the possible contribution of different structural analysis and monitoring tools to the level of knowledge on this vulnerability; **0:** Earthquakes (or other catastrophic events) are not considered in the vulnerability assessment. The hazard of earthquakes and other catastrophic events is still included in the risk assessment. No ratings will have to be given on the possible contribution of different structural analysis and monitoring tools to the level of knowledge on the vulnerability to earthquakes (or other catastrophic events).
12C(i) - 12C(iii)	**1:** Most important aim for global damage vulnerability characterisation. **2:** Second most important aim for global damage vulnerability characterisation. **3:** Least important aim for global damage vulnerability characterisation.
	Structural analysis, structural health monitoring and additional diagnosis activities
13A - 13E, 14A - 14D, 15A -15D, 16A -16F, 17A -17D, 18A -18G, 19A -19D	**0:** Irrelevant / Not considered in risk analysis; **1:** Can complement; **2:** Can contribute significantly / Essential

Appendix B. Specific questions after structural analysis and structural health monitoring

Table B.1: Questions that need to be answered to update indicators of level of knowledge and damage vulnerability after structural analysis or structural health monitoring has been carried out. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	**Question**	**Answer range**	**Case study**
	Load report		
20A	How much of the loads needed for a comprehensive evaluation were calculated?	(0 - 5)	4.75
20B	Are there areas with concerning high loading levels?	(1 - 5)	3
	Graphic statics and limit analysis		
21A, 25A*,29A†	What proportion of identified cases of interest were evaluated?	(0 - 5)	4.5, 3.5*
21B, 25B*,29B†	Are there potential cases with a precarious equilibrium?	(1 - 5)	2, 3*
	Numerical modelling (including FEM, DEM, AEM)		
22A, 26A*,30A†	What proportion of identified loading scenarios of interest were investigated?	(0 - 5)	4.5, 4*
22B, 26B*,30B†	Do the simulations reveal that parts of the structure could be vulnerable to foreseeable loading conditions?	(1 - 5)	2, 2.5*
	Dynamic structural health monitoring		
23A, 27A*,31A†	What proportion of dynamic parameters of interest have been monitored?	(0 - 5)	3, 4*
23B, 27B*,31B†	Is the monitoring duration suitable to observe the phenomena of interest?	(0 - 5)	3, 3*
23C, 27C*,31C†	Are there signs that parts of the structure could be vulnerable to foreseeable loading conditions?	(1 - 5)	3, 3*
	Static structural health monitoring		
24A, 28A*,32A†	What proportion of parameters of interest have been monitored?	(0 - 5)	3, 1*
24B, 28B*,32B†	How many years of monitoring data are available to date?	$\geq$ 0 years (0 - 5)	3.5 yrs (2.0)
24C, 28C*,32C†	What percentage of sensors are classified as evolutionary?	$\geq$ 0% (1 - 5)	8% (2.14)
24D, 28D*,32D†	What is the yearly average growth rate of all monitored crack widths classified as apparently evolutionary or evolutionary? [mm]	$\geq$ 0 mm (0 - 5)	0.034 mm (2.76)
24E, 28E*,32E†	What is the yearly average growth rate of all monitored distances classified as apparently evolutionary or evolutionary? [mm]	$\geq$ 0 mm (0 - 5)	0.073 mm (1.74)
24F, 28F*,32F†	What is the yearly average growth rate of all monitored inclinations classified as apparently evolutionary or evolutionary? [^{o}]	$\geq 0\ ^o$ (0 - 5)	0.019 ^{o} (2.5)

* Structural analysis aimed at better understanding vulnerability to earthquakes.

† Structural analysis aimed at better understanding vulnerability to other catastrophic events.

Table B.2: Description of the significance of the different values that can be attributed to each specific question related to structural analysis or structural health monitoring.

Question ref.	**Range description**
	Load report
20A	**0:** No load report; **1:** A minuscule fraction; **2:** A tiny fraction; **3:** A small fraction; **4:** A substantial fraction; **5:** All or most of the relevant loads
20B	**1:** None; **2:** A few potential areas; **3:** Several potential areas / Definitely in at least one area; **4:** Definitely in some areas; **5:** Definitely in several areas
	Graphic statics and limit analysis
21A, 25A*,29A[†]	**0:** No limit analysis; **1:** A minuscule fraction; **2:** A tiny fraction; **3:** A small fraction; **4:** A substantial fraction; **5:** All or most of the relevant cases
21B, 25B*,29B[†]	**1:** None; **2:** A few potential cases; **3:** Several potential cases / At least one definitive case; **4:** Some definitive cases; **5:** Several definitive cases
	Numerical modelling (including FEM, DEM, AEM)
22A, 26A*,30A[†]	**0:** No numerical models; **1:** a minuscule fraction; **2:** a tiny fraction; **3:** a small fraction; **4:** a substantial fraction; **5:** All or most of the relevant scenarios
22B, 26B*,30B[†]	**1:** None; **2:** A few potential cases; **3:** Several potential cases / At least one definitive case; **4:** Some definitive cases; **5:** Several definitive cases
	Dynamic structural health monitoring
23A, 27A*,31A[†]	**0:** No dynamic SHM; **1:** a minuscule fraction; **2:** a tiny fraction; **3:** a small fraction; **4:** a substantial fraction; **5:** All or most of the relevant parameters
23B, 27B*,31B[†]	**0:** No dynamic SHM; **1:** Absolutely not; **2:** With a great deal of uncertainty; **3:** With moderate uncertainty; **4:** With little uncertainty; **5:** With minimal uncertainty
23C, 27C*,31C[†]	**1:** None; **2:** A few potential indications; **3:** Several potential indications / At least one definitive indication; **4:** Some definitive indications; **5:** Several definitive indications
	Static structural health monitoring
24A, 28A*,32A[†]	**0:** No static SHM; **1:** a minuscule fraction; **2:** a tiny fraction; **3:** a small fraction; **4:** a substantial fraction; **5:** All or most of the relevant parameters
24B, 28B*,32B[†]	Specific value function
24A, 28C*,32C[†]	Specific value function
24D, 28D*,32D[†]	Specific value function
24E, 28E*,32E[†]	Specific value function
24F, 28F*,32F[†]	Specific value function

* Structural analysis aimed at better understanding vulnerability to earthquakes.

[†] Structural analysis aimed at better understanding vulnerability to other catastrophic events.

Appendix C. Specific questions after evaluation of material properties

Table C.1: Questions that need to be answered to update indicators of level of knowledge and damage vulnerability after experimental evaluation of material properties. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	Question	Answer range	Case study
	Experimental characterisation of compressive strengths of constituents		
33A	How would you rate the overall confidence level of the estimated compressive strengths?	(0 - 5)	0
33B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
33C	Are there potential estimates indicating worryingly low strengths?	(1 - 5)	NA
	Experimental characterisation of compressive strength of masonry		
34A	How would you rate the overall confidence level of the estimated compressive strengths?	(0 - 5)	0
34B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
34C	Are there potential estimates indicating worryingly low strengths?	(1 - 5)	NA
	Experimental characterisation of shear load-bearing capacity of masonry		
35A	How would you rate the overall confidence level of the estimated capacity?	(0 - 5)	0
35B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
35C	Are there potential estimates indicating worryingly low strengths?	(1 - 5)	NA
	Experimental characterisation of elastic moduli of constituents		
36A	How would you rate the overall confidence level of the estimated moduli?	(0 - 5)	0
36B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
36C	Are there potential stiffness estimates indicating material degradation?	(1 - 5)	NA
	Experimental characterisation of elastic modulus of masonry		
37A	How would you rate the overall confidence level of the estimated moduli?	(0 - 5)	2
37B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	4
37C	Are there potential stiffness estimates indicating material degradation?	(1 - 5)	2
	Experimental characterisation of composition and/or other specific properties		
38A	How would you rate the overall confidence level of the estimated properties?	(0 - 5)	4
38B	What proportion of the areas of interest have been covered by the current and previous investigations?	(0 - 5)	4
38C	Do some of the estimated properties suggest an increased vulnerability of the material to degradation or damage?	(1 - 5)	1

Table C.2: Description of the significance of the different values that can be attributed to each specific question related to experimental evaluation of material properties.

Question ref.	Range description
33A, 34A, 35A, 36A, 37A, 38A	**0:** No tests; **1:** Not confident at all; **2:** Slightly confident; **3:** Somewhat confident; **4:** Fairly confident; **5:** Completely confident
33B, 34B, 35B, 36B, 37B, 38B	**0:** No tests; **1:** a minuscule fraction; **2:** a tiny fraction; **3:** a small fraction; **4:** a substantial fraction; **5:** All or most of the relevant areas
33B, 34C, 35C, 36C, 37C, 38C	**1:** None; **2:** A few potential ones; **3:** Several potential ones / Definitely at least one; **4:** Definitely some; **5:** Definitely several

Appendix D. Specific questions after additional geometry and damage surveys

Table D.1: Questions that need to be answered to update indicators of level of knowledge and damage vulnerability after additional geometry and damage surveys. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	Question	Answer range	Case study
	Topographic surveys		
39	What proportion of the possible areas of interest have been covered by the current and previous topographic surveys?	(0 - 5)	4.5
2	Please update the global rating of the level of knowledge on the geometry of the structure	(0 - 5)	4.5
	Borescope inspections and/or excavation pits		
40	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
2	Please update the global rating of the level of knowledge on the geometry of the structure	(0 - 5)	NA
	Impact-echo testing		
41	What proportion of the possible areas of interest have been covered by the current and previous impact-echo tests?	(0 - 5)	0
2	Please update the global rating of the level of knowledge on the geometry of the structure	(0 - 5)	NA
	More accurate or extensive survey of damages		
42	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	4
3	Please update the global rating of the level of knowledge on existing damages	(0 - 5)	4
	Option to update initial damage vulnerability assessment		
8	Based on available historical information, damage inspections, and reasonable engineering judgement, please rate the perceived susceptibility of the structure to experience significant damage due to progressive collapse mechanisms.	(1 - 5)	-
9B	Based on the information available about past performance to historical earthquakes, as well as the evidence on the structure in terms of damage, please rate how concerning is the perceived vulnerability of the structure to earthquakes.	(1 - 5)	-
10B	Based on available historical information, damage inspections, and reasonable engineering judgement, please rate how concerning is the perceived vulnerability of the structure to other potential catastrophic events.	(1 - 5)	-

Table D.2: Description of the significance of the different values that can be attributed to each specific question related to additional geometry and damage surveys.

Question ref.	Range description
39, 40, 41, 42	**0:** No additional surveys, inspections or tests; **1:** A minuscule fraction; **2:** A tiny fraction; **3:** A small fraction; **4:** A substantial fraction; **5:** All of the relevant areas
2, 3, 8, 9B, 10B	See Table A.2

Appendix E. Specific questions after additional diagnosis activities for the assessment of material quality

Table E.1: Questions that need to be answered to update indicators of level of knowledge and damage vulnerability after carrying out activities involving the assessment of material quality. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	**Question**	**Answer range**	**Case study**
	Borescope inspections and/or excavation pits		
43A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	1
43B	How would you rate the overall integrity and quality of the masonry material based on the investigations?	(1 - 5)	3
	Sonic pulse velocity testing (including tomography)		
44A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	3.5
44B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the pulse velocity tests?	(1 - 5)	4
	Ultrasonic pulse velocity testing		
45A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
45B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the pulse velocity tests?	(1 - 5)	NA
	Surface penetrating radar testing		
46A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	4
46B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the radar tests?	(1 - 5)	4
	Infrared thermography		
47A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	4
47B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the thermography tests?	(1 - 5)	3
	Rebound hammer		
48A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
48B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the rebound tests?	(1 - 5)	NA
	Other specific tests for evaluating material quality and condition		
49A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
49B	How would you rate the overall integrity and quality of the masonry material based on the outcome of the tests?	(1 - 5)	NA

Table E.2: Description of the significance of the different values that can be attributed to each specific question related to the assessment of material quality.

Question ref.	**Range description**
43A, 44A, 45A, 46A, 47A, 48A, 49A	**0:** No tests; **1:** A minuscule fraction; **2:** A tiny fraction; **3:** A small fraction; **4:** A substantial fraction; **5:** All or most of the relevant areas
43B, 44B, 45B, 46B, 47B, 48B, 49B	**1:** Very poor quality, large variability; **2:** Poor quality ; **3:** Moderate quality; **4:** High quality; **5:** Very high quality, very uniform material

Appendix F. Specific questions after in situ tests of actual loading and boundary conditions

Table F.1: Questions that need to be answered to update indicators of level of knowledge and damage vulnerability after carrying out in situ tests of actual loading and boundary conditions. The column case study refers to the investigation made by the authors on Mallorca cathedral.

Question ref.	Question	Answer range	Case study
	Flatjack in-situ tests of stress levels		
50A	What proportion of the possible areas of interest have been covered by the current and previous investigations?	(0 - 5)	0
50B	Are there many areas with concerning high stress levels?	(1 - 5)	NA
	Ambient vibration tests		
51A	What proportion of the dynamic parameters of interest have been covered by the current and previous investigations?	(0 - 5)	4
51B	Are there signs that parts of the structure could be vulnerable to foreseeable loading conditions?	(1 - 5)	2
	Geotechnical surveys		
52A	What proportion of investigations required for a comprehensive characterisation of the soil-structure interaction effects have been carried out?	(0 - 5)	4
52B	Are there signs of possible active mechanisms or specific vulnerabilities related to soil-structure interaction or to site effects?	(1 - 5)	1.5
	Other specific tests		
53A	What proportion of identified parameters of interest have been covered by the current and previous investigations?	(0 - 5)	1
53B	Are there signs that parts of the structure could be vulnerable to foreseeable loading conditions?	(1 - 5)	2

Table F.2: Description of the significance of the different values that can be attributed to each specific question related to in situ tests of actual loading and boundary conditions.

Question ref.	Range description
50A, 51A, 52A, 53A	**0:** No tests; **1:** A minuscule fraction; **2:** A tiny fraction; **3:** A small fraction; **4:** A substantial fraction; **5:** All or most of the relevant areas
50B, 51B, 52B, 53B	**1:** None; **2:** A few potential indications; **3:** Several potential indications / At least one definitive indication; **4:** Some definitive indications; **5:** Several definitive indications

Appendix G. Detailed application to case studies

Table G.3: Detailed calculation of the Level of Knowledge index for case studies. Scores shown have already been transformed through application of the appropriate value functions.

Question ref.	**Criteria considered in Level of Knowledge index**	**Mallorca cathedral**		**Sant Cugat monastery**		**Lloberola tower**		**Santa Maria de Guimerà church**	
		Weight	**Score**	**Weight**	**Score**	**Weight**	**Score**	**Weight**	**Score**
1A	Construction process	1%	4.63	1%	4.63	1%	4.44	1%	4.63
1B	Previous structural alterations	1%	4.24	1%	4.63	1%	4.44	1%	4.63
1C	Past structural interventions	1%	4.63	1%	4.24	1%	3.79	1%	4.24
1D	Past damage events	1%	4.24	1%	4.24	1%	4.13	1%	3.41
Historical information and documentation		**4%**	**4.44**	**4%**	**4.44**	**4%**	**4.20**	**4%**	**4.23**
2	Overall quality of information on geometry	3%	4.24	3%	3.84	3%	4.44	3%	4.24
3	Overall quality of information on damage	3%	4.63	3%	3.84	3%	4.73	3%	3.41
39, 40, 41, 42	Additional activities *(topographic surveys, borescope inspections, excavation pits, impact echo testing, more damage surveys)*	1%	4.44	1%	1.71	1%	0.00	1%	0.00
Geometry and damage surveys		**7%**	**4.44**	**7%**	**3.54**	**7%**	**3.94**	**7%**	**3.29**
20A, 21A, 22A, 23A, 23B, 24A, 24B	Structural analysis and SHM for understanding vulnerability to **progressive collapse mechanisms** *(load reports, limit analysis, numerical modelling, dynamic and static SHM)*	41.2%	4.06	41.2%	2.33	41.2%	0.00	38.0%	1.52
25A, 26A, 27A, 27B, 28A, 24B	Structural analysis and SHM for understanding vulnerability to **earthquakes** *(limit analysis, numerical modelling, dynamic and static SHM)*	11.8%	3.65	11.8%	1.04	11.8%	0.00	4.1%	0.00
29A, 30A, 31A, 31B, 32A, 24B	Structural analysis and SHM for understanding vulnerability to **other catastrophic events** *(limit analysis, numerical modelling, dynamic and static SHM)*	0.0%	0.00	0.0%	0.00	0.0%	0.00	10.9%	0.00
Structural analysis and SHM		**53%**	**3.97**	**53%**	**2.04**	**53%**	**0.00**	**53%**	**1.09**
33A, 33B	Compressive strength - constituents	1.25%	0.00	1.25%	0.00	1.25%	0.00	1.4%	0.00
34A, 34B	Compressive strength - masonry	2.50%	0.00	2.50%	0.00	2.50%	0.00	2.9%	0.00
35A, 35B	Shear capacity- masonry	2.50%	0.00	2.50%	0.00	2.50%	0.00	2.9%	0.00
36A, 36B	Elastic modulus - constituents	1.25%	0.00	1.25%	0.00	1.25%	0.00	0.0%	0.00
37A, 37B	Elastic modulus - masonry	1.25%	3.41	1.25%	0.00	1.25%	0.00	1.4%	0.00
38A, 38B	Other specific material properties	1.25%	4.24	1.25%	3.41	1.25%	0.00	1.4%	0.00
Material properties		**10%**	**0.96**	**10%**	**0.43**	**10%**	**0.00**	**10%**	**0.00**
4A	Material quality from visual inspections	1.70%	2.49	1.70%	2.49	1.70%	4.13	1.70%	2.96
43A	Material quality from borescope inspections	1.38%	1.42	1.66%	0.00	0.00%	0.00	5.53%	0.00
44A	Sonic pulse velocity testing	2.77%	3.84	3.32%	0.00	5.53%	0.00	2.77%	0.00
45A	Ultrasonic pulse velocity testing	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
46A	Surface penetrating radar	2.77%	4.24	1.66%	0.00	0.00%	0.00	0.00%	0.00
47A	Infrared thermography	1.38%	4.24	1.66%	0.00	2.77%	0.00	0.00%	0.00
48A	Rebound hammer	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
49A	Other NDT/MDT of material quality	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
Material quality		**10%**	**3.44**	**10%**	**0.42**	**10%**	**0.70**	**10%**	**0.50**
50A	Flatjack in/situ tests of stress levels	2.7%	0.00	2.7%	0.00	0.0%	0.00	4%	0.00
51A	Ambient vibration tests	5.3%	4.24	5.3%	0.00	5.3%	0.00	4%	0.00
52A	Geotechnical surveys	5.3%	4.24	5.3%	2.96	10.7%	0.00	8%	0.00
53A	Other specific tests	2.7%	1.42	2.7%	0.00	0.0%	0.00	0%	0.00
Actual loading and boundary conditions		**16%**	**3.07**	**16%**	**0.99**	**16%**	**0.00**	**16%**	**0.00**
Level of Knowledge index			**3.52**		**1.75**		**0.51**		**1.03**

Table G.4: Detailed calculation of the Damage Vulnerability index for case studies. Scores shown have already been transformed through application of the appropriate value functions.

Question ref.	**Criteria considered in Damage Vulnerability index**	**Mallorca cathedral**		**Sant Cugat monastery**		**Lloberola tower**		**Santa Maria de Guimerà church**	
		Weight	**Score**	**Weight**	**Score**	**Weight**	**Score**	**Weight**	**Score**
7	**Need for urgent action**	**0%**	**0.00**	**0%**	**0.00**	**0%**	**0.00**	**92.40%**	**3.78**
6A, 6B	**Lack of maintenance**	**3%**	**1.36**	**3%**	**1.36**	**4%**	**1.74**	**0.33%**	**2.28**
8, 20B, 21B, 22B, 23C, 24C, 24D, 24E, 24F	Vulnerability to progressive collapse mechanisms	47%	2.43	47%	2.66	64%	4.00	4.48%	3.00
25B, 26B, 27C, 24C, 24D, 24E, 24F	Vulnerability to earthquakes	14%	2.60	14%	2.49	18%	4.50	0.49%	3.50
29B, 30B, 31C, 24C, 24D, 24E, 24F	Vulnerability to other catastrophic events	0%	1.00	0%	1.00	0%	2.50	1.28%	3.50
	Vulnerability to specific hazards	**61%**	**2.47**	**61%**	**2.62**	**82%**	**4.11**	**6.24%**	**3.14**
33C	Compressive strength - constituents	0%	0.00	0%	0.00	0%	0.00	0%	0.00
34C	Compressive strength - masonry	0%	0.00	0%	0.00	0%	0.00	0%	0.00
35C	Shear capacity- masonry	0%	0.00	0%	0.00	0%	0.00	0%	0.00
36C	Elastic modulus - constituents	0%	0.00	0%	0.00	0%	0.00	0%	0.00
37C	Elastic modulus - masonry	5%	2.00	0%	0.00	0%	0.00	0%	0.00
38C	Other specific material properties	5%	1.00	10%	1.00	0%	0.00	0%	0.00
	Material properties	**10%**	**1.50**	**10%**	**1.00**	**0%**	**0.00**	**0%**	**0.00**
4B	Material quality from visual inspections	2%	2.23	10%	2.23	14%	3.48	1.03%	3.48
43B	Material quality - borescope inspections	1%	2.23	0%	0.00	0%	0.00	0%	0.00
44B	Sonic pulse velocity testing	3%	1.36	0%	0.00	0%	0.00	0%	0.00
45B	Ultrasonic pulse velocity testing	0%	0.00	0%	0.00	0%	0.00	0%	0.00
46B	Surface penetrating radar	3%	1.36	0%	0.00	0%	0.00	0%	0.00
47B	Infrared thermography	1%	2.23	0%	0.00	0%	0.00	0%	0.00
48B	Rebound hammer	0%	0.00	0%	0.00	0%	0.00	0%	0.00
49B	Other NDT/MDT of material quality	0%	0.00	0%	0.00	0%	0.00	0%	0.00
	Material quality	**10%**	**1.75**	**10%**	**2.23**	**14%**	**3.48**	**1.03%**	**3.48**
50B	Flatjack in/situ tests of stress levels	0.0%	0.00	0%	0.00	0%	0.00	0%	0.00
51B	Ambient vibration tests	6.4%	2.00	0%	0.00	0%	0.00	0%	0.00
52B	Geotechnical surveys	6.4%	1.50	16%	3.00	0%	0.00	0%	0.00
53B	Other specific tests	3%	2.00	0%	0.00	0%	0.00	0%	0.00
	Actual loading and boundary conditions	**16%**	**1.80**	**16%**	**3.00**	**0%**	**0.00**	**0%**	**0.00**
	Damage Vulnerability index		**2.16**		**2.44**		**3.92**		**3.73**

Table G.5: Detailed calculation of the Damage Risk index for case studies. Scores shown have already been transformed through application of the appropriate value functions.

Question ref.	**Criteria considered in Damage Risk index**	**Mallorca cathedral**		**Sant Cugat monastery**		**Lloberola tower**		**Santa Maria de Guimerà church**	
		Weight	**Score**	**Weight**	**Score**	**Weight**	**Score**	**Weight**	**Score**
	Damage Vulnerability	**50%**	**2.16**	**50%**	**2.44**	**50%**	**3.92**	**50%**	**3.73**
9A	Seismic Hazard	10%	1.92	10%	1.92	10%	2.15	10%	1.92
10A	Hazard of other catastrophic events	10%	1.00	10%	1.00	10%	1.00	10%	2.00
11	Fire Hazard	5%	2.00	5%	2.00	5%	1.00	5%	2.50
	Hazard	**25%**	**1.57**	**25%**	**1.57**	**25%**	**1.46**	**25%**	**2.07**
5A	Cultural value	12.5%	4.00	12.5%	3.50	12.5%	3.00	12.5%	2.00
5B	Level of usage	12.5%	4.00	12.5%	3.50	12.5%	1.00	12.5%	2.00
	Exposure	**25%**	**4.00**	**25%**	**3.50**	**25%**	**2.00**	**25%**	**2.00**
	Damage Risk index		**2.47**		**2.49**		**2.83**		**2.88**

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