Impact of Maintenance, Rehabilitation, and Other Interventions on Functionality of Heritage Buildings

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Abstract: The maintenance of heritage buildings can be extremely complex; usually, practitioners face many difficult decisions regarding when and how to intervene. The data recovered over time of the conservation and rehabilitation of heritage buildings could represent a new input to aid stakeholders' decision-making concerning an efficient planning of the maintenance activities to carried out during the buildings' service life. This study evaluated the impact of maintenance activities in the functionality of heritage buildings through the analysis of historical records concerning the maintenance activities performed on a set of heritage buildings from the 13th and 14th centuries through the 21st century. A sample of 390 historical records were analyzed, recovered from a set of 20 parish churches in the province of Seville in southern Spain. This study assessed the variations observed in the functional service life (buildings' performance) of the heritage buildings under analysis according to the different interventions and maintenance actions performed over time. The knowledge of the past behavior of the constructions over time and the impact of the different maintenance activities performed allowed finding some patterns in the data. The results obtained in this study, and the lessons learned from past actions, allow promoting the increase of the stakeholders' knowledge concerning the impact of maintenance activities in heritage buildings, thus aiding the adoption of more technically informed and sustainable maintenance actions in the future. **DOI: 10.1061/(ASCE)CF.1943-5509.0001271.** *© 2019 American Society of Civil Engineers.*

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Introduction

The inadequate performance of constructions during their service life usually entails an extremely high economic and social burden. Wekesa et al. (2010) noted that the performance of heritage constructions is a critical component of the social-economic strength of current societies in Europe and in Spain. In European countries, around 50% of all buildings' refurbishments in cities and towns are linked, in some way, with the conservation of the built heritage (Balaras et al. 2005).

Currently, on a worldwide scale, the built heritage is aged and with clear signs of degradation. The current situation is due to the lack of codes for the continued management of buildings during their service life, the lack of investment in the rehabilitation of the built heritage, and the lack of knowledge and tools to aid the decisions to intervene. Therefore, it is essential to develop innovative tools and methods to evaluate the buildings' serviceability and maintainability (Torres and Ruiz 2007) in order to promote the adoption of effective and sustainable maintenance planning and strategies for the preservation of heritage buildings.

Naturally, all buildings and components will deteriorate over time, with a progressive degradation of their performance condition until the instant at which they are no longer capable of fulfilling the users' needs and requirements (Gaspar and Brito 2005). The preservation of the buildings' performance condition for a longer period through the prevention or mitigation of the degradation of their constructive elements depends on decisions involving preventive maintenance tasks (Chen et al. 2013). The lack of decision-making tools for the optimization of preventive maintenance activities in heritage buildings lead to excessive and even unnecessary costs due to the performance of inefficient and inadequate maintenance operations (Silva et al. 2016).

In order to minimize the excessive costs associated with reactive maintenance activities, stakeholders are currently adopting predictive or condition-based maintenance plans. The primary objective of maintenance activities in buildings is to ensure that their systems and components always function adequately, with the intention of achieve optimum performance during their life cycle (Reffat et al. 2004). Predictive maintenance is based on the assessment of the assets' condition, intending to minimize unexpected failures and consequently reduce maintenance costs (Wu et al. 2007). In this sense, maintenance activities must be seen as an investment opportunity that needs to be optimized and not as a cost that must be minimized.

In terms of heritage building maintenance, there are currently numerous constructions that remain particularly expensive to preserve, both environmentally and economically (Martínez-Rocamora et al. 2016). The optimization of maintenance strategies is a complex subject that depends on an accurate evaluation of the buildings' performance and a reliable prediction of their service life (Morgado et al. 2017). Moreover, subjective aspects that are crucial for the decision-making process, such as the users' perception, needs, and

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expectations, and the funds available, should also be considered in the definition of maintenance policies. Alba-Rodríguez et al. (2017) mentioned that the key criteria for decision-making in regard to the buildings' renovation are the investment costs, the buildings' performance conditions, and the existing regulations. However, in heritage buildings such as those analyzed in this study, cultural, social, historic, aesthetic, and religious aspects should also be considered.

Research Objectives

To address these concerns, the approach presented in this study is a new contribution to aid the decision-making processes regarding the definition of preventive maintenance strategies, considering historical records recovered over centuries. The data included information related to different kind of interventions (maintenance actions, refurbishment, or rehabilitation) performed on historical buildings from the 13th and 14th centuries through the 21st century. A sample of 390 historical records was collected from a set of 20 parish churches in the province of Seville, Spain.

This paper proposes a methodological analysis of the impact of maintenance actions and other interventions on the functional service life of heritage buildings. Few studies have evaluated the functional service life of buildings. Various authors (Macías-Bernal et al. 2014; Ibáñez et al. 2016; Prieto et al. 2018) have proposed new methodologies for predicting the functional service life of heritage buildings, which this study specifically applied to religious buildings in Seville, Spain.

This study uses a numerical index, fuzzy building service life improved ($FBSL_{2.0}$) to evaluate the functionality level of the heritage buildings analysed. This index is calculated through a fuzzy inference system (FIS) based on expert knowledge related to the management of built heritage. In the $FBSL_{2.0}$ index, the functionality of a given building is evaluated not only based on its conservation condition (or physical degradation) but also considering other 16 variables that evaluate the functional performance of the building, including the buildings' vulnerability (e.g., environmental exposure conditions), static-structural risks (e.g., load-state modifications), atmospheric risks (e.g., rainfall) and anthropic risks (e.g., heritage value). Therefore, this index evaluates the serviceability of a building, i.e., its ability to perform the function for which it was designed (Masters and Brandt 1989), as well as the capability of fulfilling specific performance requirements according to the experts consulted. Davis and Szigeti (1999) defined serviceability of buildings as their capability to support the activities or functions of users and owners, when required. Currently, in contemporary societies, the demands of building occupants are more and more dynamic and demanding (Blok et al. 2002), requiring that the building and its components are capable of constantly adapting to fulfil users' criteria.

This study allows obtaining some guidance in terms of the evolution of the main maintenance and conservation actions carried out in a set of heritage buildings, with analogous constructive features, and their influence on the serviceability of the buildings over centuries. Learning from past lessons is crucial for the definition of future preventive conservation plans (Carter and Bramley 2002). This study provides support for the decision-making of predictive maintenance actions in order to understand the weak points of this type of building which should be carefully examined during periodic inspections. The analysis of the preservation and maintenance activities performed over the last centuries will help define the success of the different strategies adopted, and also the lack of success or the impact of inadequate practices, evaluating the main preservation actions that have significant influence on the functionality of the buildings over time.

Materials and Methods

Location and Constructive Characterization of Sample

This study is based on available data regarding the state of conservation of 20 heritage buildings in the province of Seville, Spain, in an area of 14,000 km^2. The geographical region extends from the mouth of the Guadalquivir River in the southwest to the Sierra Norte Natural Park in the north. The buildings analyzed have religious features, with a great variety in terms of their monumental and artistic value. In terms of their construction style, all the buildings had homogeneous characteristics, sharing similar cultural and regulatory aspects (Fig. 1). These churches were built in the Mudejar-Gothic, Renaissance, and Baroque styles between the thirteenth–fourteenth and eighteenth centuries (Ortiz et al. 2017). A large number of churches were erected in a short time, and the available workers were mainly Mudejar (subjugated Moors), who were familiar with other construction techniques, such as timber roofs and brick walls. This gave rise to the Mudejar-Gothic style, with churches whose most representative points (presbytery and portals) are built of stone, following the Gothic style, whereas the body of the church has brick walls (Girón et al. 2017).

The structure of the buildings under analysis is constituted of thick brick walls around the perimeter and in the central pillars, which are organized in two rows parallel to the longitudinal axis of the church (Girón et al. 2017; Ortiz and Ortiz 2016). The three naves of the church are covered with a coffered timber structure. The central nave has two slopes and a greater height. The two lateral naves have a single slope and a more reduced height. The main chapel is covered with a carved stone structure, symbolizing the relevance of the enclosure (Vigil-Escalera 1991).

The facades have a very simple composition and are especially sober, without decorative elements, and they only break horizontal monotony with simple windows made of stone and with small dimensions (Macías-Bernal et al. 2014).

Generally, the bell tower is located close to the main façade. The towers of these churches normally use the mosque constructions previously existing on the sites. The main material used is brick. The floor plan of the tower is quadrangular and remarkably slender.

Data Set Collection

In this study, the historical data were gathered from (1) documentary files owned by the Archdiocese of Seville, with information concerning the maintenance activities and performance condition of the churches analyzed; (2) a company specializing in the construction sector, which collaborated with the Archdiocese of Seville in the performance of some conservation works (Archives of Archdiocese of Seville 2016); (3) organizational strategic plans, relevant standards, annual reports, and other types of documents and evidence (books and academic/applied papers) with relevant information for the characterization of the churches under analysis in the last centuries; and (4) semistructured interviews with the key stakeholders (decision-makers responsible for the maintenance operations) of buildings and with priests. The collection of historical data contained around 390 records, an average of approximately 19 historical records per church (García 2014; Carmona 2014; Charneco 2014; López 2015; Prieto et al. 2017b). A fieldwork survey was also performed because these in situ observations enabled a deeper understanding of the built environment, historical resources, and property conditions (Prieto et al. 2018). The analysis of historical records, chronologically ordered, allows determining the functional performance of buildings over the last centuries. Prieto et al. (2016a) applied the FIS and the Delphi method to

Fig. 1. Case studies considered: ID1, San Pablo, Aznalcázar; ID2, Santa María de las Nieves, Benacazón; ID3, San Miguel Arcángel, Castilleja del Campo; ID4, Nuestra Señora de la Asunción, Huévar del Aljarafe; ID5, Santa María la Mayor, Pilas; ID6, Nuestra Señora de la Granada, La Puebla del Río; ID7, Nuestra Señora de la Estrella, Coria del Río; ID8, Los Sagrados Corazones, San Juan de Aznalfarache; ID9, Nuestra Señora de la Estrella, Palomares del Río; ID10, Nuestra Señora de la Antigua, Almensilla; ID11, Nuestra Señora de la Granada, Guillena; ID12, Santa María de Gracia, Almadén de la Plata; ID13, San Juan Bautista, El Castillo de las Guardas; ID14, Divino Salvador, El Ronquillo; ID15, Santa María de las Nieves, La Algaba; ID16, San Julián, Sevilla; ID17, San Lorenzo, Sevilla; ID18, Ómnium Sanctorum, Sevilla; ID19, San Román, Sevilla; ID20, Santa Marina, Sevilla. (Images by A. J. Prieto.)

obtain quantitative results from qualitative information. This approach provides output data on the functional performance condition of each construction at each time for which enough records are available. The Delphi method is usually used to reduce experts' subjectivity; this study established a fuzzy Delphi method (FDM) assessment methodology that effectively measures the performance of buildings over time.

Functional Service Life Model

Fuzzy logic is an innovative technique to model real-world phenomena, especially when the phenomena under analysis are vague and uncertain in nature, such as the modeling of the functional service life of heritage buildings. The fuzzy set theory, introduced by Zadeh (1965), allows translating the linguistic vagueness of some considerations related to the maintenance and conservation of the built heritage into mathematical models. In contrary to a classical set (crisp set), in which the membership degree of an element is crisp $[0, 1]$, the fuzzy set allows a given element to belong to a given set with a given degree of membership, ranging over a unit interval of 0 to 1.

The fuzzy inference model proposed in this study encompasses four main stages: (1) fuzzification, (2) inference, (3) base of knowledge, and (4) defuzzification. In this study, the functional service life prediction model proposed, called fuzzy building service life extended, was based on a methodology previously established by Macías-Bernal et al. (2014), which was based on the assessment of the functional degradation of constructions, translated by a ranking in terms of priorities of interventions. This method expresses the global functional level of a building considering a total of 17 input variables: 5 variables related to the buildings' vulnerability (Table 1) and 12 related to external hazards (Table 2).

Therefore, to apply this method, it is necessary to quantify all the input parameters of the fuzzy system. Prieto et al. (2016a, b) proposed a functional degradation scale for heritage buildings (parish churches) based on the risk-management standard ISO 31000: 2011 (ISO 2009), with three levels of performance (Table 3).

After this condition, the methodology suggests an urgent intervention (in a short period) in terms of preserving the functionality of the buildings at acceptable performance levels. In this work, the functionality of buildings is estimated by a fuzzy inference system, implemented through open-access software Xfuzzy 3.0.

Table 1. Fuzzy model input factors and valuation description of vulnerabilities

Identifier	Vulnerability	Quantitative valuation (optimum/medium/bad)	Qualitative valuation
v_1	Geological location	(1.0/2.5/4.0)	Good/acceptable/unfavorable ground conditions in terms of stability
v_2	Roof design	(1.0/4.5/8.0)	Fast/normal/complex and slow evacuation of water
v_3	Environmental conditions	—	Building without or between complex constructions around it
v_4	Constructive system	—	Uniform or heterogeneous characteristics of constructive system
v_5	Preservation	—	Optimal/normal/neglected state of conservation

Table 2. Fuzzy model input factors and valuation description of external hazards

Identifier	Hazard	Quantitative valuation (optimum/medium/bad)	Qualitative valuation
Static-structural			
r_6	Load state modification	(1.0/4.5/8.0)	Apparently/symmetric and balanced/disorderly modification
r_7	Live loads	—	Live load below/equal to/higher than the original level
r_8	Ventilation	—	Natural cross-ventilation in all or only in some areas
r_9	Facilities	—	All/some facilities in use or not ready for use
r_{10}	Fire	—	Low/medium/high fire load in relation with combustible structure
r_{11}	Inner environment	—	Low/medium/maximum level of health, cleanliness, and hygiene of the building's spaces
Atmospheric			
r_{12}	Rainfall and wind	(1.0/4.5/8.0)	Area with low/medium/maximum annual rainfall
r_{13}	Temperature variation	—	Area with low/medium/maximum temperature differences
Anthropic			
r_{14}	Population growth	(1.0/4.5/8.0)	Population growth greater than 15%/0%/ − 5%
r_{15}	Heritage value	—	Properties with great/average/low historical value
r_{16}	Furniture value	—	Sociocultural and liturgical appreciation (high/average/low value)
r_{17}	Occupancy	—	High/medium/low occupancy of building

Table 3. Levels of performance based on the risk-management standard

Condition	Description
A	The level of risk is regarded as negligible and the building presents an adequate functional level.
B	The costs and benefits of preventive measures must be taken into account and balanced.
C	The level of risk is considered to be intolerable, with a high priority of intervention.

Source: Data from ISO (2011).

Fuzzification

This stage comprises the transformation of crisp values into grades of membership for linguistic terms of fuzzy sets. Gaussian-type membership functions are regularly considered to be the most suitable for modeling the performance conditions of the buildings, because a nonzero value can be reached at all points of the function (Ross 2010).

The fuzzification process assigns a degree of membership to each element in the universe of discourse U, in which the fuzzy set is described

$$\mu_A : U \rightarrow [0, 1] \tag{1}$$

Knowledge-Based and Fuzzy Inference Rules

The base rule is a collection of fuzzy control rules, comprising linguistic labels, representing the expert knowledge of the controlled system. Mamdani's fuzzy model, one of the most accepted algorithms, is used in this study (Mamdani and Assilian 1975). A total of 15 experts in heritage building management were consulted during the model's design stage. The professional experts consulted were professors of preservation, experts involved in the rehabilitation and pathology of buildings, architects, archaeologists, civil engineers, and managers of heritage buildings (Macías-Bernal et al. 2014; Prieto et al. 2017b). A Delphi methodology was used to treat the answers obtained from the expert surveys. The fuzzy logic inference model, known as a generalized modus ponens, was established in the $\mathrm{FBSL}_{2.0}$ model [Eq. (2)], together with its hierarchical structure (Ibáñez et al. 2016)

$$\mathrm{Rule(a)} = \text{if } X \text{ is } A \text{ and } Y \text{ is } B, \quad \text{then } Z \text{ is } C \tag{2}$$

where A, B, and C = linguistic values characterized by fuzzy sets. The use of fuzzy sets provides the generalization of the knowledge used to explain the performance system. The if part of the rule is called the premise and the then part of the rule is called the consequence. A total of 354 rules were used, and the combinations of input membership functions (premise part) and output membership functions (consequence part) was made through expert-knowledge decisions. Fig. 2 shows the hierarchical structure of the fuzzy model ($\mathrm{FBSL}_{2.0}$) and the set of rules.

Defuzzification

The defuzzification procedure was used to obtain a (crisp) value representing the fuzzy information produced by the inference system. Moreno-Velo et al. (2007) recommended the center of the area (COA), which is one of the most common and successful methods for defuzzification processes

$$\mathrm{FBSL}_{2.0} = \frac{\sum_i y_i \cdot \mu_B(y_i)}{\sum_i \mu_B(y_i)} \tag{3}$$

The method addresses a semiqualitative index, based on the evaluation by specialists of each building analyzed. The model's uncertainty is addressed as a Type B uncertainty (Taylor and Kuyatt 2000), i.e., it is based on the technical-scientific judgment of 15 experts specializing in the maintenance and conservation of heritage buildings.

Results and Discussion

Historical Records Evolution by Period

The historical data collected in this study cover different kinds of interventions (maintenance actions, refurbishment, or rehabilitation) performed on heritage buildings from the 13th and 14th centuries through the 21st century. The data collected in terms of the maintenance and refurbishment actions are characterized by the progressive addition of historical records (conservation activities) (Lucchi 2018) over the centuries. Over the centuries and closer to the 21st century, more information was recorded and made available in historical archives.

Fig. 3 shows the global overview and the evolution of the principal maintenance actions, generalized interventions, natural hazards (e.g., earthquakes), and anthropic risk (e.g., fires and periods of war or confiscation) to which the set of heritage buildings selected is subject. The statistical analysis of the maintenance and

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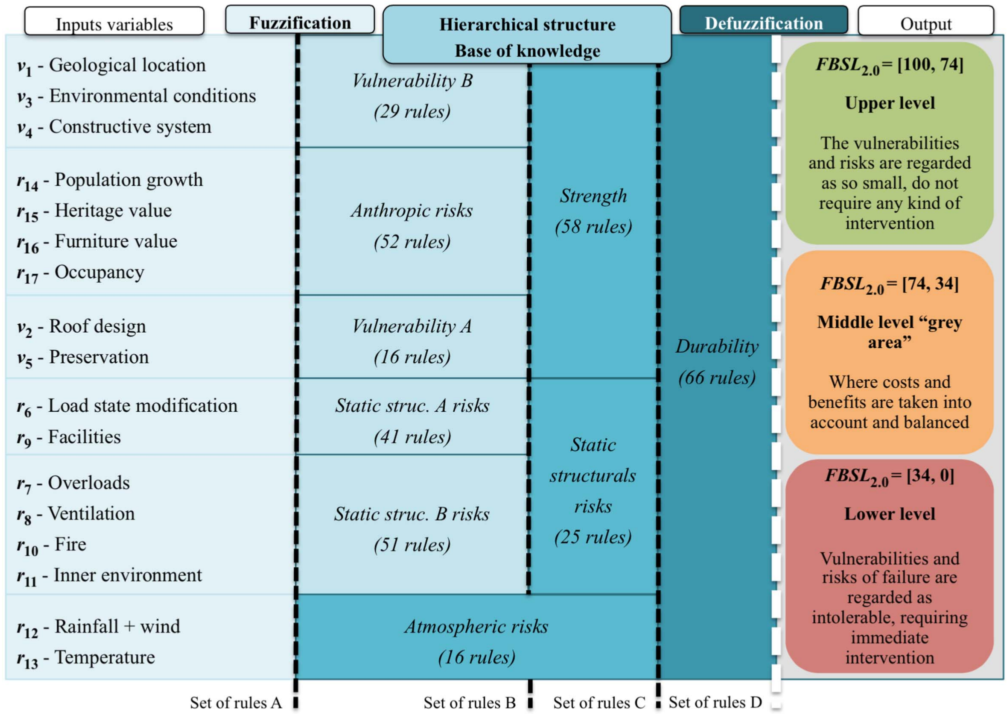

Fig. 2. Structure of the fuzzy building service life extended model.

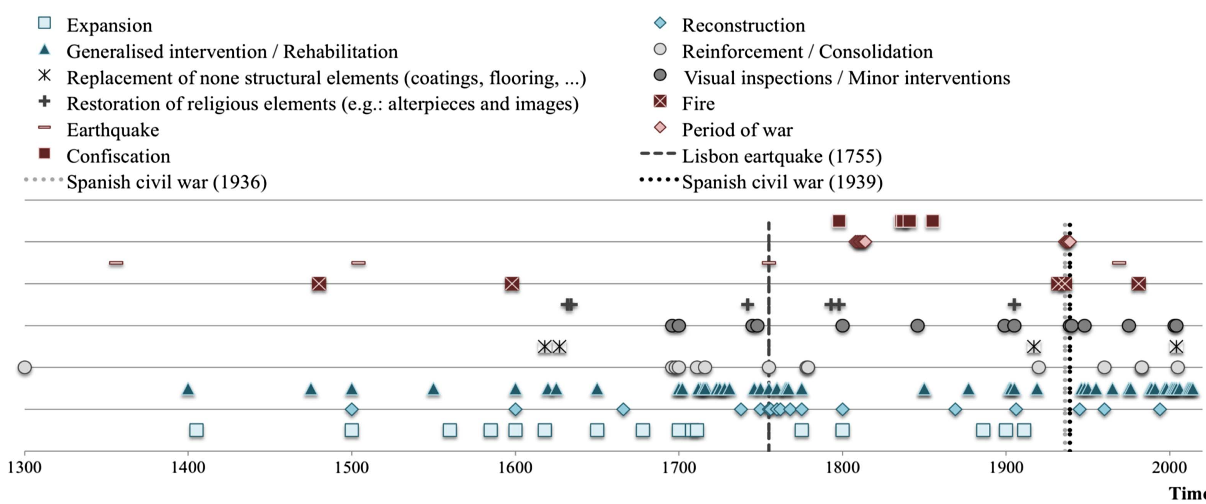

Fig. 3. Global overview of the main buildings' interventions considered over time, including catastrophic events.

conservation actions carried out over the centuries in the heritage buildings analyzed is presented in Fig. 4. The next sections organize the information registered into four periods, and provide some historical explanations to understand why certain decisions were made in relation to maintenance actions, as well as a pattern of intervention based on historical, political, and natural hazards contexts (Prieto et al. 2015).

1300–1599: Generalized Interventions and Expansion Works

From 1300 until 1599, the main maintenance activities performed were related to (1) the reinforcement or consolidation (100% in the fourteenth century) of the heritage buildings; (2) generalized interventions and rehabilitation (67% and 33% in the fifteenth and sixteenth centuries, respectively); expansion works (33% in the fifteenth century and 50% in the sixteenth century); and, finally, reconstruction of the heritage buildings represented 17% of activities (carried out between 1500 and 1599) (García 2014; Carmona 2014; Charneco 2014; López 2015). The activities related to reconstruction of the buildings were quite scarce despite being registered after two earthquakes and two fires in the case studies considered (Fig. 3) during this period. This situation could be affected by the loss of records during this period.

1600–1799: Maintenance Activities and Natural Risks

In the seventeenth century, records related to preservation and maintenance activities increased significantly. The key actions outlined by the records were related to generalized intervention/rehabilitation (23%), expansion works (23%), and the restoration of altarpieces (12%). On the other hand, visual inspections/minor interventions (6%) had the smallest role (Fig. 4).

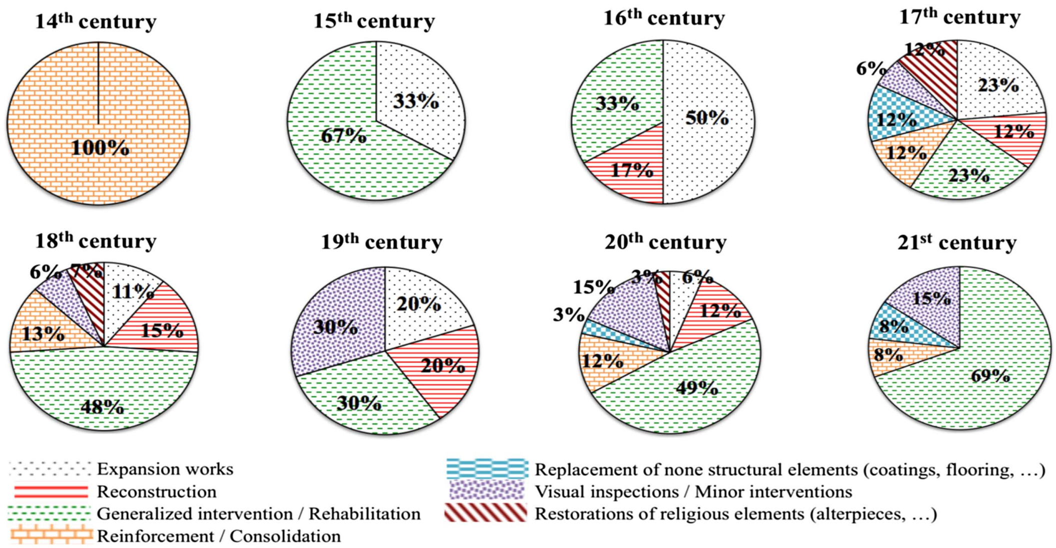

Fig. 4. Statistical analysis of the maintenance and conservation actions performed in the heritage buildings analyzed.

During the eighteenth century, southwestern Europe experienced a significant seismic incident on November 1, 1755 (Lisbon earthquake). This seism, with an estimated magnitude of 8.7 on the Richter scale, killed 60,000 people in southern Iberia and northwestern Morocco and generated a 5–10-m-high tsunami wave (Gutscher 2004). The epicenter of this incident was in the Atlantic Ocean, approximately 300 km from the city of Lisbon, Portugal. This scenario was directly related to historical records dating from after 1755, for which documents verify great damage and even destruction of historical buildings in the south of the Iberian Peninsula due to the Lisbon earthquake (Silva and Henriques 2015; Conde et al. 2015). Therefore, there was a peak in the reconstruction of churches soon after the earthquake of 1755, but before that, this action was not very relevant; of course, with the increase of the age of the churches (or when a catastrophic event occurs), this action is beginning to be relevant again.

1800–1899: Confiscations and Napoleonic Invasion

In the 19th century, the Napoleonic invasion (1810–1812) and the ecclesiastical confiscation of 1836 (Confiscation of Mendizábal) represented a great loss of cultural heritage in Spain (Charneco 2014; López 2015). For this century, information concerning the performance of maintenance actions is scarce due to these historical events. These kinds of actions, i.e., confiscations, were promoted by the Spanish government's seizure and sale of religious properties from the late eighteenth century to the early twentieth century (Hernández Navarro et al. 2008). It was a historical, economic, and social process beginning with the so-called Confiscation of Godoy in 1798. After this event, the Confiscation of Espartero (1841) and the Confiscation of Madoz (1855) followed (Fig. 3).

These confiscations damaged several buildings of artistic interest, such as churches and monasteries; for these reasons it was not possible to obtain much more information about the heritage buildings under analysis during this historical period. Much information was completely lost and even destroyed (Castro Correa 2014). For this reason, the number of generalized interventions and rehabilitation activities (30%) was higher than in previous periods. Reconstruction and expansion works corresponded to 20% of the total activities of this period (Fig. 4), and some activities related to visual inspections (30%) were also performed, thus promoting the adoption of maintenance actions in subsequent periods.

1900–2017: Anthropic Risks

During the 20th century and the first part of the 21st century, the main conservation activities were related to anthropic risks, such as periods of war. These events had a direct effect on the decline of the functional performance of the parish churches under analysis, and also had a huge impact at a social, cultural, and political level in the Spanish society of the time (Fernandes 2015). Generalized interventions and rehabilitation actions represented the most common activities in the 20th and 21st centuries, 49% and 69%, respectively (Fig. 4). The reconstructions (12%) and reinforcement activities performed during the twentieth century are clearly correlated with the effects of wars in Spanish territory. The activity with less relevance in this period was the restoration of religious elements, because it was not a priority once it did not contribute to the structural safety of buildings. Some expansion works (6%) were performed in the twentieth century, interrupted by conflicts in which some parish churches in the province of Seville were burned some years before the war (1936–1939) (Prieto et al. 2017b). Visual inspections and minor interventions (15%) were mainly associated with cleaning actions or the localized repair of defects and anomalies of the buildings' components (Bortolini and Forcada 2017).

Fig. 5 illustrates the influence of disastrous events, as war, on the loss of functional performance on five of the heritage buildings under analysis. Sørensen and Viejo-Rose (2015) stated that "the impact of conflicts on heritage is thus not limited to the conflict itself, for cultural heritage is equally used and transformed during post-conflict phases when efforts are aimed at the recovery of society."

Impact of Maintenance Activities on Functional Degradation Condition over Time

The maintenance of heritage buildings is managed without adequate tools and reliable information that allow optimizing the funds available for the maintenance tasks. The analysis of historical records and the application of the $FBSL_{2.0}$ model allow obtaining some guidance concerning the preventive conservation of built heritage. During the analysis stage, some comments were obtained from different stakeholders and companies with more than 25 years of experience in the management of maintenance activities in heritage buildings. Fig. 6 presents the evolution of the maintenance actions performed from the 13th through the 21st century. Based on the

Fig. 5. Five case studies after an anthropic risk (Spanish Civil War, 1936–1939). IDs are defined in Fig. 1. (Images courtesy of University of Seville.)

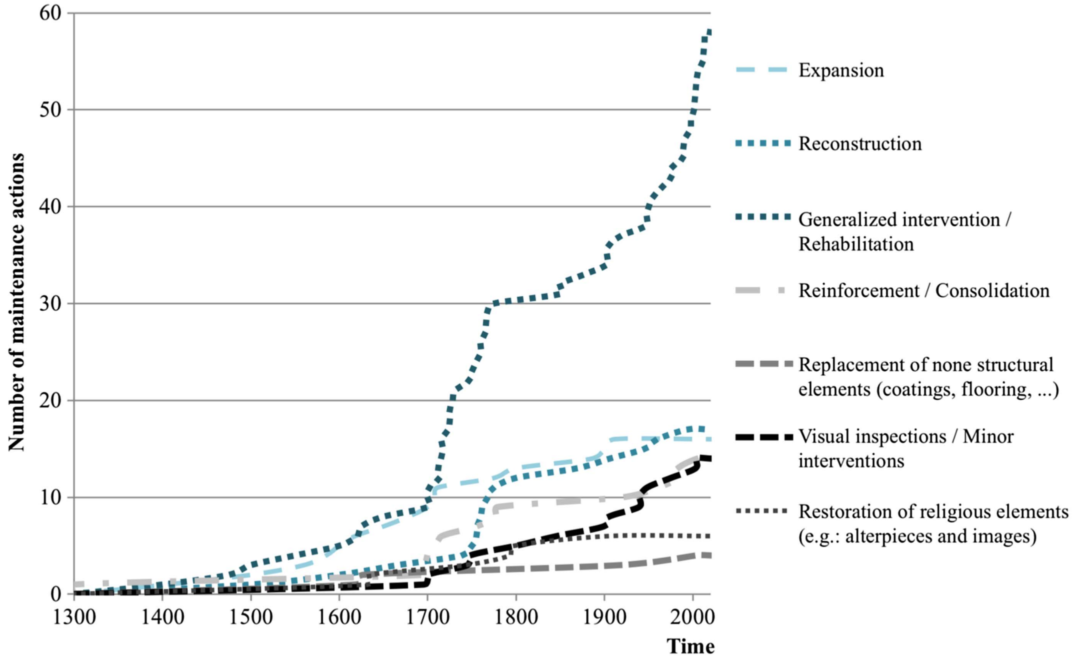

Fig. 6. Number of maintenance actions from 13th through 21st centuries.

analysis performed in this study, the following main conclusions can be drawn:

- In the first centuries after their construction (Fig. 6), churches are not subject to relevant interventions and rehabilitation actions, because it is expected that the buildings still have adequate functional levels and do not yet show any significant deterioration that justifies intervention. Moreover, users' and stakeholders' demands have changed over time, i.e., in ancient times, the lack of funds, the occurrence or threat of wars, and less-demanding levels of functional performance naturally led to a lower number of interventions and rehabilitation actions. Nevertheless, it is important to note that there is always a possibility that some maintenance or even important rehabilitation actions could have been performed that were not been recorded in the historical records collected (Charneco 2014; López 2015). Prieto et al. (2017b), after an exhaustive analysis of historical records, concluded that in 85% of the buildings under analysis, the time of refurbishment actions after a disastrous event was between 1 and 20 years. This result is a first approximation of the possible path in terms of intervention time in historical constructions in Seville (Spain) after disastrous incidents, revealing that usually, after a calamity, stakeholders recognize the importance of intervening in order to restore the functionality of the building. In some cases, when funds are not available, the restoration occurs many years later, which also reveals the subjective criteria that affect the decision to intervene.
- Generalized interventions and rehabilitation actions are the most registered actions in each historical period and increase exponentially after catastrophic events caused by natural risks (Lisbon earthquake, 1755) and anthropic risks (Spanish Civil War, 1936–1939) (Fig. 6). Sometimes, important reconstruction actions are only proposed after catastrophic events, such as earthquakes (Ceci et al. 2010). Furthermore, in the historical records analyzed, activities related to reconstruction increased exponentially after the huge earthquake in the middle of the eighteenth century. Stakeholders more easily recognize the need for intervention after a catastrophic event or when a building has an extremely high and unacceptable level of functional deterioration, often already compromising the users' safety. After a catastrophic event, the functionality of buildings is usually restored in a short period.
- For this reason, the number of generalized interventions increased significantly after the Lisbon earthquake in 1755 (Baeza et al. 2018). There was a peak in the reconstruction of churches soon after the earthquake of 1755 due to the recognized urgency of intervention in these buildings. Before this event, generalized interventions were not a common practice or a significant action for the buildings analyzed, according to the historical records. Naturally, with the increase of the age of the churches, this action (or when a catastrophic event occurs) is becoming more prominent and relevant for the preservation of the heritage buildings.

- The other maintenance and preservation actions have a homogeneous behavior, except the restoration of religious elements and the replacement of none structural elements (Fig. 6), which had the smallest number of actions (García 2014; Carmona 2014) because they are not directly linked to the buildings' functionality.

The decision to intervene is usually related to the inability of a building to fulfil the stakeholders' requirements. Although in an unconscious manner and without tools to measure the level of functionality of buildings, the stakeholders usually decide to intervene when they consider (subjectively) that the building presents unacceptable degradation levels or that it is obsolescent from a functional point of view. Therefore, it seems relevant to correlate the historical data regarding the different maintenance actions performed over the centuries and the functionality indexes of the buildings in each period of intervention (through the quantification of the FBSL level). Table 4 presents the functionality levels of the heritage buildings before and after maintenance activities, leading to the following conclusions:

- The reconstruction is usually carried out when the building has lower $FBSL_{2.0}$ indexes; an average value of 28.2 points (Table 4) was obtained for the churches analyzed that were subjected to this rehabilitation action (Prieto et al. 2017a). In the sample analyzed, all the churches had a bad functionality level according to the visual and physical scale in Fig. 7 before their reconstruction, making clear to the decision makers the need to intervene.
- As expected, reconstruction was the action with the highest impact in the functionality level of the heritage buildings analyzed, implying a higher variation in the functionality level, allowing the transition of those buildings from a bad functionality condition to a medium or good functionality condition. Reconstruction corresponds to major repair and is related to actions of local replacement and preventive treatment. In general terms, the interventions were oriented to buildings' covers (roofs), bell towers, and façades, generally encompassing a high economic burden.
- The generaliaed intervention or rehabilitation actions also had a relevant impact on the buildings' functionality (Table 4). These actions are those that occur more often, and usually when a medium or bad functionality level is achieved, thus revealing that maintenance is essentially corrective rather than preventive (Fig. 6).
- Replacement is commonly connected with actions to completely replace a material/elements when the area affected cannot be recovered. These activities are extremely conditioned by the physical degradation of buildings and components (Bortolini and Forcada 2017) and are usually related to the replacement of interior claddings, paintings, or interior pavements.

Table 4. Functionality levels of heritage buildings before and after maintenance activities

Kind of intervention	Average $FBSL_{2.0}$ Before intervention	Average $FBSL_{2.0}$ After intervention	$\Delta FBSL_{2.0}$
Expansion works	63.0	79.4	16.3
Reconstruction	28.2	61.8	33.6
Generalized intervention/rehabilitation	53.3	73.4	20.1
Reinforcement/consolidation	57.8	74.5	16.7
Replacement of none structural elements (e.g., coatings and flooring)	68.8	81.6	12.9
Visual inspections/minor interventions	64.0	76.1	12.1
Restorations of religious elements (e.g., altarpieces)	76.4	76.4	0.0

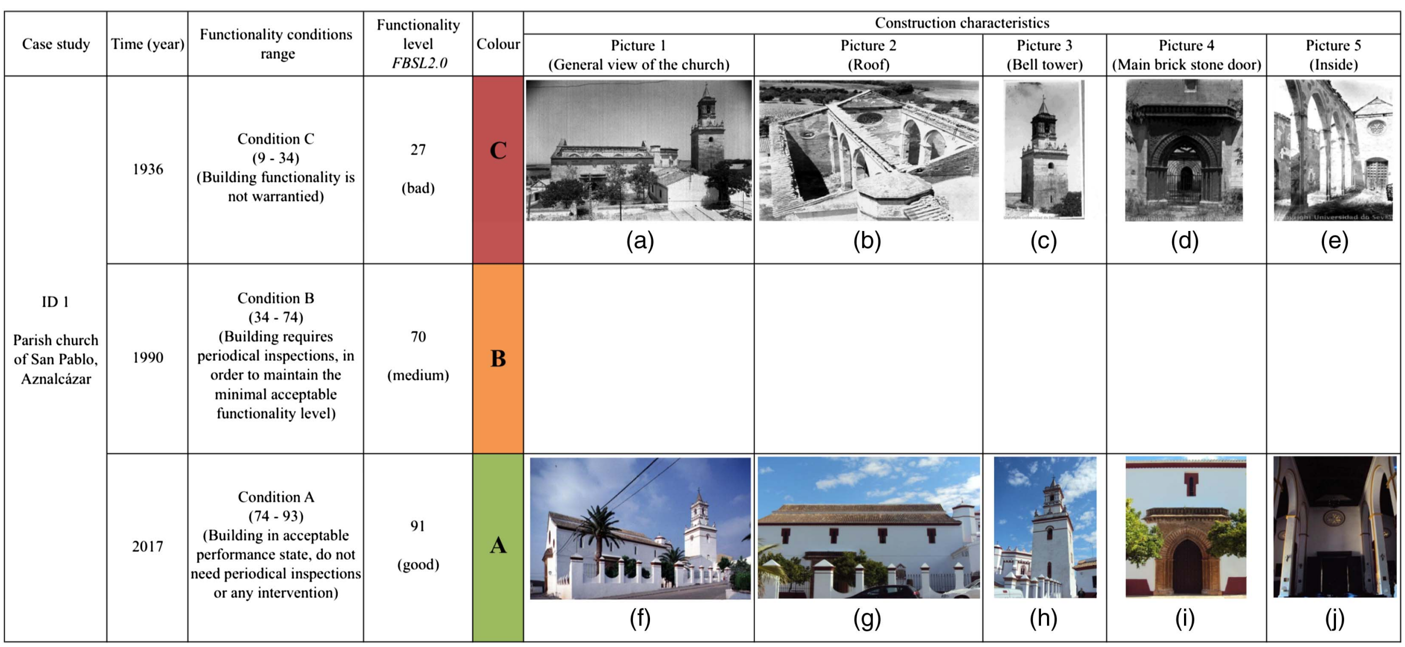

Fig. 7. Example of one church in the three functional degradation conditions over time. [Images (a–e) courtesy of University of Seville; (f–j) by A. J. Prieto.]

Table 5. Historical recorded evolution of case study ID1, San Pablo parish church (Aznalcázar, Seville)

Year	Recorded information	$v1$	$v2$	$v3$	$v4$	$v5$	$r6$	$r7$	$r8$	$r9$	$r10$	$r11$	$r12$	$r13$	$r14$	$r15$	$r16$	$r17$	$FBSL_{2.0}$
1400	Construction.	1.00	1.50	1.50	1.25	1.50	1.25	1.25	1.50	1.50	2.50	1.75	2.50	3.00	2.00	2.00	2.00	2.00	91
1479	Visual inspections. Date of the oldest existing church before it was burned.	1.00	2.00	2.00	1.50	1.75	1.50	1.50	1.75	1.50	2.75	1.75	2.50	3.00	2.00	2.00	2.00	2.00	87
1480	Fire. Conservation state after the burning of the church.	1.00	6.00	5.50	5.00	6.00	2.50	4.00	4.00	5.00	6.00	4.75	2.50	3.00	2.00	6.00	6.00	5.00	26
1500	Reinforcement and consolidation. The façades of the Epistle and the façade of Los Novios date from this year.	1.00	4.50	4.00	4.00	4.50	2.25	2.00	2.50	3.00	2.75	2.50	2.50	3.00	2.50	5.00	5.00	4.00	40
1637	Generalized interventions and rehabilitation including restoration of religious elements (e.g., altarpieces and images).	1.00	1.75	1.75	1.50	1.50	1.50	1.75	2.00	2.00	2.75	2.50	2.50	3.00	1.50	1.75	1.75	1.75	88
1750	Visual inspections. Before the 1755 Lisbon earthquake. Conservation state of the building under normal exposure conditions.	1.00	2.50	2.50	2.75	2.50	2.25	2.50	2.50	3.00	3.25	2.75	2.50	3.00	1.75	1.75	1.75	1.75	65
1755	Lisbon earthquake.	1.00	4.00	3.75	4.00	4.50	3.00	3.25	3.00	3.25	3.75	3.25	2.50	3.00	2.50	3.00	3.00	2.75	42
1760	After the 1755 Lisbon earthquake. Minor interventions related to maintenance work in the building.	1.00	3.75	3.50	3.50	4.00	3.00	3.25	3.00	3.25	3.75	3.25	2.50	3.00	2.50	3.00	3.00	2.75	47
1763	Rehabilitation works. Crowned by a Baroque-style pyramidal spire decorated with tiles designed by Ambrosio de Figueroa.	1.00	2.75	2.50	2.50	2.75	2.25	2.25	2.50	2.50	2.50	2.75	2.50	3.00	2.00	2.75	2.75	2.00	68
1765	Beginning of a major rehabilitation of the church. Crowned by a bell tower when Pedro de Silva carried out major reform work in this church.	1.00	2.50	2.50	2.50	2.50	2.25	2.25	2.50	2.50	2.50	2.75	2.50	3.00	2.00	2.75	2.75	2.00	75
1767	Generalized intervention and rehabilitation are finished.	1.00	1.75	1.50	1.75	1.50	2.00	2.00	2.25	2.25	2.25	2.50	2.50	3.00	2.00	2.75	2.75	2.00	86
1932	Fire. On September 7, 1932, the temple was burned and the roof covering the central nave and aisles was lost. In the fire, altarpieces and religious images that were inside the building also burned.	1.00	6.00	4.75	5.50	5.00	3.00	3.50	3.50	3.75	6.00	5.00	2.50	3.00	3.00	6.00	6.00	4.50	30
1936	Spanish Civil War.	1.00	5.50	4.50	5.00	4.00	3.00	3.50	3.50	3.75	6.00	5.00	2.50	3.00	3.00	5.00	6.00	4.50	27
1941	Reinforcement and consolidation.	1.00	3.25	3.25	3.25	3.00	1.50	1.25	1.50	1.75	1.50	1.75	2.50	3.00	2.00	3.00	3.00	2.00	58
1945	Reconstruction. On June 29, 1945, the new church was opened. It was, first and foremost, a replica of the previous church but with far fewer works of art, which were gradually restored in subsequent years.	1.00	1.25	1.25	1.50	1.25	1.50	1.25	1.50	1.75	1.50	1.75	2.50	3.00	2.00	2.00	2.00	2.00	91
1990	Visual inspection/minor interventions. Fig. 7 gives a rough idea of the state of functionality of the building in the early 1990s.	1.00	2.50	1.75	1.50	2.50	1.50	1.25	1.50	1.75	1.50	1.75	2.50	3.00	2.00	2.00	2.00	2.00	70
2003	Visual Inspection and evaluation of the humidity affecting the false ceiling of the parish office and check the longitudinal fissure halfway up the transitable roof, through which water probably entered the building. Correction of the anomalies detected.	1.00	2.25	1.75	1.50	2.00	2.00	1.50	1.25	2.00	1.75	2.00	2.50	3.00	1.75	2.00	2.00	2.00	86
2004	Visual inspection to check the finishing of the paintings and review the exterior coatings, as well as the condition of the waterproofing of the presbytery vaults and the rear annex.	1.00	3.00	2.50	2.00	2.00	1.75	1.50	1.75	2.00	1.75	2.00	2.50	3.00	1.75	2.00	2.00	2.00	86
2005	Reinforcement of the wooden roof beams due to termite attack.	1.00	2.50	2.50	2.00	2.00	1.75	1.50	1.75	2.00	1.75	2.00	2.50	3.00	1.75	2.00	2.00	2.00	87
2007	Inspection to evaluate the detachment of the plaster ceiling in one of the halls of the parish church. (Previous work was carried out on the façade, roofing, and supporting structure of the church).	1.00	2.00	2.00	1.75	2.00	1.75	1.50	1.75	2.00	1.75	2.00	2.50	3.00	1.75	2.00	2.00	2.00	87
2011	Generalized intervention. A staircase and access ramp were built, the flooring was repaired, and a sewage system was installed in the courtyards of San Pablo de Aznalcázar parish church.	1.00	2.75	2.50	2.00	2.00	1.75	1.50	1.75	1.75	1.75	2.00	2.50	3.00	1.75	2.00	2.00	2.00	90
2017	Current condition of the building in 2017.	1.00	1.25	1.25	1.50	1.25	1.50	1.25	1.50	1.75	1.50	1.75	2.50	3.00	2.00	2.00	2.00	2.00	91

- The restoration of religious elements (such as altarpieces) occurred in buildings with an average index of $FBSL_{2.0}$ of 76 points (Table 4), thus revealing that this action is independent of the functionality level of the church, but instead is due to other reasons (of an aesthetic or religious nature). As expected, the restoration of religious elements and the replacement of nonstructural elements were the actions with the lowest impact in terms of the global performance of the buildings, and thus had lower relevance to the level of functionality of the churches, an average value of 0.0 points (Table 4).

Fig. 7 provides a practical example (a real parish church selected from the case studies analyzed) to illustrate the different functional condition levels according to the $FBSL_{2.0}$ model, as well as a description of the state of conservation of the church in each of the three functional degradation conditions over time. The functional conditions proposed are based on Prieto et al. (2019) and vary from C (buildings in which the functionality is no longer guaranteed) to A (buildings with an acceptable functionality condition) (Fig. 7). Table 5 presents 22 historical records collected for the San Pablo parish church, and provides a time-dependent functional index of this case study from 1400 to 2017. In situations in which the professional experts cannot find enough records related to the state of conservation of a building, they must evaluate a heritage construction by considering an average condition using the available information.

This information can be very useful for the definition of future preventive conservation plans (Carter and Bramley 2002). The adoption of successful future maintenance actions can only be achieved through the analysis of previous activities in heritage constructions, identifying previous maintenance works and the effects of these actions on the functional performance of these buildings. Prieto et al. (2017b) established that for buildings with a functional index lower than 34 points, restoration actions should be performed in the next 5–10 years to preserve their historical features over time. These kinds of analysis related to adequate maintenance activities will ensure that heritage buildings are treated with care in order to maintain their historic, cultural, and religious features for as long as possible at adequate levels of performance (Goodwin et al. 2009).

Conclusions

This study analyzed a total of 390 historical records concerning the maintenance activities carried out in a set of 20 heritage buildings (churches) in South Spain. This study estimated the impact of different maintenance strategies on the functional service life (building performance) of heritage buildings over time.

To evaluate the functional level of the buildings under analysis, the $FBSL_{2.0}$ model was used. This model was established based on a fuzzy inference system, defined through an expert-knowledge survey of several experts with several years of experience in the maintenance sector. A functional degradation ranking of Condition A (buildings with no visible degradation), Condition B (buildings requiring periodical inspections), and Condition C (buildings with generalized degradation) was established and correlated with the functionality index ($FBSL_{2.0}$).

The correlation of the historical data recovered and the functionality level of the heritage buildings analyzed allows obtaining the following main conclusions:

- During the first centuries after their construction, churches are not subject to relevant maintenance/rehabilitation actions.
- Moreover, during several decades, and especially in times of economic constraints, maintenance activities were sparse, not a priority, or were not performed at all.
- Catastrophic events due to natural risks and anthropic risks promote higher levels of degradation in the heritage buildings. After catastrophic events due to natural risks, the stakeholders perceive the relevance and urgency of intervention, and relevant actions are performed soon after the events.
- Anthropic risks (e.g., wars) strongly influence the loss of functionality of heritage buildings, not only compromising the buildings' safety but also destroying cultural and religious elements, which cannot be replaced.
- Generalized interventions and rehabilitation actions were the most-registered actions in each historical period, producing a relevant impact on the buildings' functionality. The results obtained revealed that these actions are usually performed after the buildings reach an inadequate level of performance, revealing that the maintenance activities performed are essentially corrective rather than preventive, thus encompassing a higher economic burden, while allowing the building to degrade to inadequate performance levels.
- The restoration of religious elements (e.g., altarpieces) does not influence the functionality level of the church, and therefore this action is usually performed for aesthetic or religious reasons.

These analyses find patterns in data that can assist in planning future maintenance activities. This knowledge can help in understanding the past functionality level of the buildings, identifying the most common maintenance actions (and their impact on the buildings' functionality), thus predicting the future behavior of the buildings analyzed. The results obtained can be used to amplify the stakeholders' knowledge concerning the preventive conservation of heritage buildings. This study can be extended to other buildings and components and can also be adjusted to different environmental contexts.

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References

Alba-Rodríguez, M. D., A. Martínez-Rocamora, P. González-Vallejo, A. Ferreira-Sánchez, and M. Marrero. 2017. "Building rehabilitation versus demolition and new construction: Economic and environmental assessment." *Environ. Impact Assess. Rev.* 66: 115–126. https://doi.org/10.1016/j.eiar.2017.06.002.

Archives of Archdiocese of Seville. 2016. "General archives of the Archbishopric of Seville." Accessed January 4, 2018. http://www.archisevilla.org/documentacion/archivo-historico/.

Baeza, F. J., S. Ivorra, D. Bru, and F. B. Varona. 2018. "Structural health monitoring systems for smart heritage and infrastructures in Spain." In *Mechatronics for cultural heritage and civil engineering*, 271–294. Cham, Switzerland: Springer.

Balaras, C. A., K. Droutsa, E. Dascalaki, and S. Kontoyiannidis. 2005. "Deterioration of European apartment buildings." *Energy Build.* 37 (5): 515–527. https://doi.org/10.1016/j.enbuild.2004.09.010.

Blok, R., F. V. Herwijnen, A. Kozlowski, and S. Wolinski. 2002. "Service life and life cycle of building structures." In *Proc., COST C12 Seminar* *on Improvement of Building's Structural Quality by New Technologies*. Brussels, Belgium: European Commission.

Bortolini, R., and N. Forcada. 2017. "Discussion about the use of Bayesian networks models for making predictive maintenance decisions." In Vol. 1 of *Proc., Joint Conf. on Computing in Construction (JC3)*, 973–980. Heraklion, Crete, Greece: Heriot-Watt Univ.

Carmona, T. 2014. "Vulnerability and risk factors in parishes temples of the Archpriesthood of Pilas." [In Spanish.] B.Sc. thesis, Construction Management, Univ. of Seville.

Carter, R. W., and R. Bramley. 2002. "Defining heritage values and significance for improved resource management: An application to Australian tourism." *Int. J. Heritage Stud.* 8 (3): 175–199. https://doi.org/10.1080/13527250220000/18895.

Castro Correa, A. 2014. "The reconstruction of early medieval Spanish manuscript sources." *Early Medieval Europe* 22 (1): 69–87. https://doi.org/10.1111/emed.12039.

Ceci, A. M., A. Contento, L. Fanale, D. Galeota, V. Gattulli, M. Lepidi, and F. Potenza. 2010. "Structural performance of the historic and modern buildings of the University of L'Aquila during the seismic events of April 2009." *Eng. Struct.* 32 (7): 1899–1924. https://doi.org/10.1016/j.engstruct.2009.12.023.

Charneco, L. 2014. "Análisis e influencia de las series temporales y los factores de riesgo y vulnerabilidad en distintos edificios del Arciprestazgo de Itálica." [In Spanish.] B.Sc. thesis, Construction Management, Univ. of Seville.

Chen, H. M., C. C. Hou, and Y. H. Wang. 2013. "A 3D visualized expert system for maintenance and management of existing building facilities using reliability-based method." *Expert Syst. Appl.* 40 (1): 287–299. https://doi.org/10.1016/j.eswa.2012.07.045.

Conde, D. A., M. J. Telhado, M. A. V. Baptista, and R. M. Ferreira. 2015. "Severity and exposure associated with tsunami actions in urban waterfronts: The case of Lisbon, Portugal." *Nat. Hazard.* 79 (3): 2125–2144. https://doi.org/10.1007/s11069-015-1951-z.

Davis, G., and F. Szigeti. 1999. "Are facilities measuring up? Matching building capabilities to functional needs?" In *Durability of building materials and components*, edited by M. A. Lacasse and D. J. Vanier, 1856–1866. Ottawa: Institute for Research in Construction.

Fernandes, T. 2015. "Rethinking pathways to democracy: Civil society in Portugal and Spain, 1960s–2000s." *Democratization* 22 (6): 1074–1104. https://doi.org/10.1080/13510347.2014.901966.

García, F. J. 2014. "Clima y conservación: Series temporales de cinco templos del Aljarafe." [In Spanish.] B.Sc. thesis, Construction Management, Univ. of Seville.

Gaspar, P. L., and J. D. Brito. 2005. "Assessment of the overall degradation level of an element, based on field data." In *10 DBMC Int. Conf. on Durability of Building Materials and Components*. Delft, Netherlands: CIB: International Council for Research and Innovation in Building and Construction.

Girón, S., L. Álvarez-Morales, and T. Zamarreño. 2017. "Church acoustics: A state-of-the-art review after several decades of research." *J. Sound Vib.* 411: 378–408. https://doi.org/10.1016/j.jsv.2017.09.015.

Goodwin, C., J. M. Ingham, and G. Tonks. 2009. "Identifying heritage value in URM buildings." *SESOC J.* 22 (2): 16–28.

Gutscher, M.-A. 2004. "What caused the great Lisbon earthquake?" *Science* 305 (5688): 1247–1248. https://doi.org/10.1126/science.1101351.

Hernández Navarro, F. J., F. J. Campese Gallego, and P. Ybáñez Worboys. 2008. "La propiedad urbana en Sevilla: distribución y desamortización en el ocaso del Antiguo Régimen." *Baética: Estudios de arte, geografía e historia* 30: 333–350.

Ibáñez, A. J. P., J. M. M. Bernal, M. J. C. de Diego, and F. J. A. Sánchez. 2016. "Expert system for predicting buildings service life under ISO 31000 standard: Application in architectural heritage." *J. Cult. Heritage* 18: 209–218. https://doi.org/10.1016/j.culher.2015.10.006.

ISO. 2009. *Risk management: Principles and guidelines*. ISO 31000. Geneva: ISO.

ISO. 2011. *Buildings and constructed assets—Service life planning. Part 1: General principles and framework*. ISO 15686-1. Geneva: ISO.

López, P. 2015. "Análisis de los factores de riesgo y vulnerabilidad a través de series temporales de cinco Iglesias mudéjares." [In Spanish.] B.Sc. thesis, Construction Management, Univ. of Seville.

Lucchi, E. 2018. "Review of preventive conservation in museum buildings." *J. Cult. Heritage* 29: 180–193. https://doi.org/10.1016/j.culher.2017.09.003.

Macías-Bernal, J. M., J. M. Calama-Rodríguez, and M. J. Chávez-de Diego. 2014. "Prediction model of the useful life of a heritage building from fuzzy logic." *Informes de la Construcción* 66 (533): 1–11.

Mamdani, E. H., and S. Assilian. 1975. "An experiment in linguistic synthesis with a fuzzy logic controller." *Int. J. Man Mach. Stud.* 7 (1): 1–13. https://doi.org/10.1016/S0020-7373(75)80002-2.

Martínez-Rocamora, A., J. Solís-Guzmán, and M. Marrero. 2016. "Toward the ecological footprint of the use and maintenance phase of buildings: Utility consumption and cleaning tasks." *Ecol. Indic.* 69: 66–77. https://doi.org/10.1016/j.ecolind.2016.04.007.

Masters, L. W., and E. Brandt. 1989. "Systematic methodology for service life prediction of building materials and components." *Mater. Struct.* 22 (5): 385–392. https://doi.org/10.1007/BF02472509.

Moreno-Velo, F. J., I. Baturone, A. Barriga, and S. Sánchez-Solano. 2007. "Automatic tuning of complex fuzzy systems with Xfuzzy." *Fuzzy Sets Syst.* 158 (18): 2026–2038. https://doi.org/10.1016/j.fss.2007.03.006.

Morgado, J., I. Flores-Colen, J. de Brito, and A. Silva. 2017. "Maintenance planning of pitched roofs in current buildings." *J. Constr. Eng. Manage.* 143 (7): 05017010. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001316.

Ortiz, R., and P. Ortiz. 2016. "Vulnerability index: A new approach for preventive conservation of monuments." *Int. J. Archit. Heritage* 10 (8): 1078–1100. https://doi.org/10.1080/15583058.2016.1186758.

Ortiz, R., P. Ortiz, M. A. Vázquez, and J. M. Martín. 2017. "Integration of georeferenced informed system and digital image analysis to assess the effect of cars pollution on historical buildings." *Constr. Build. Mater.* 139: 320–333. https://doi.org/10.1016/j.conbuildmat.2017.02.030.

Prieto, A. J., M. J. Chávez, M. A. Garrido-Vizuete, J. M. Macías-Bernal, and F. J. Alejandre. 2016a. "Time series on functional service life of buildings using fuzzy Delphi method." In *Proc., 16th Int. Conf. on Computational and Mathematical Methods in Science and Engineering (CMMSE 2016)*. Cádiz, Spain: Univ. of Cádiz.

Prieto, A. J., J. M. Macías-Bernal, M. J. Chávez, and F. J. Alejandre. 2017a. "Fuzzy modeling of the functional service life of architectural heritage buildings." *J. Perform. Constr. Facil.* 31 (5): 04017041. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001021.

Prieto, A. J., J. M. Macías-Bernal, and M.-J. Chávez. 2015. "Series temporales de factores principales para la conservación preventiva del patrimonio." In *5o Congreso de Patología y Rehabilitación de Edificios*, Porto.

Prieto, A. J., A. Silva, J. de Brito, and F. J. Alejandre. 2016b. "Functional and physical service life of natural stone claddings." *J. Mater. Civ. Eng.* 28 (12): 04016150. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001663.

Prieto, A. J., A. Silva, J. de Brito, and J. M. Macías-Bernal. 2018. "Serviceability of facade claddings." *Build. Res. Inf.* 46 (2): 179–190.

Prieto, A. J., A. Silva, J. de Brito, J. M. Macías-Bernal, and F. J. Alejandre. 2017c. "Multiple linear regression and fuzzy logic models applied to the functional service life prediction of cultural heritage." *J. Cult. Heritage* 27: 20–35. https://doi.org/10.1016/j.culher.2017.03.004.

Prieto, A. J., A. Silva, J. de Brito, J. M. Macías-Bernal, and F. J. Alejandre. 2017b. "The influence of pathological situations on churches' functionality: An approach based on historical records." *Int. J. Archit. Heritage* 11 (4): 566–587.

Prieto, A. J., V. Vásquez, A. Silva, A. Horn, F. J. Alejandre, and J. M. Macías-Bernal. 2019. "Protection value and functional service life of heritage timber buildings." *Build. Res. Inf.* 47 (5): 567–584. https://doi.org/10.1080/09613218.2017.1404827.

Reffat, R. M., J. Gero, and W. Peng. 2004. "Using data mining on building maintenance during the building life cycle." In *Proc., 38th Australian and New Zealand Architectural Science Association (ANZASCA) Conf.*, 91–97. New Zealand: Architectural Science Association.

Ross, T. J. 2010. *Fuzzy logic with engineering applications*. Hoboken, NJ: Wiley.

Silva, A., J. de Brito, and P. L. Gaspar. 2016. “Methodologies for service life prediction of buildings: With a focus on façade claddings.” In *Green energy and technology*. New York: Springer.

Silva, H. E., and F. M. A. Henriques. 2015. “Preventive conservation of historic buildings in temperate climates: The importance of a risk-based analysis on the decision-making process.” *Energy Build.* 107: 26–36. https://doi.org/10.1016/j.enbuild.2015.07.067.

Sørensen, M. L. S., and D. Viejo-Rose, eds. 2015. *War and cultural heritage*. Cambridge: Cambridge University Press.

Taylor, B. N., and C. E. Kuyatt. 2000. “Guidelines for evaluating and expressing the uncertainty of NIST measurement results.” Accessed January 4, 2018. http://physics.nist.gov/cuu/Uncertainty/index.html.

Torres, M. A., and S. E. Ruiz. 2007. “Structural reliability evaluation considering capacity degradation over time.” *Eng. Struct.* 29 (9): 2183–2192. https://doi.org/10.1016/j.engstruct.2006.11.014.

Vigil-Escalera P. M. 1991. “Iglesias mudéjares sevillanas de los siglos XIII, XIV y XV: Propuesta para su restauración, conservación y mantenimiento.” [In Spanish.] Ph.D. thesis, Dept. of Architectural Construction II, Univ. of Seville.

Wekesa, B. W., G. S. Steyn, and F. A. O. Otieno. 2010. “The response of common building construction technologies to the urban poor and their environment.” *Build. Environ.* 45 (10): 2327–2335. https://doi.org/10.1016/j.buildenv.2010.04.019.

Wu, S. J., N. Gebraeel, M. A. Lawley, and Y. Yih. 2007. “A neural network integrated decision support system for condition-based optimal predictive maintenance policy.” *IEEE Trans. Syst. Man Cybern. Part A Syst. Humans* 37 (2): 226–236. https://doi.org/10.1109/TSMCA.2006.886368.

Zadeh, L. 1965. “Fuzzy sets.” *Inf. Control* 8 (3): 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X.